UPCYCLING INVASIVE SPECIES TO ADDRESS SOCIAL ISSUES: DEVELOPING A COMPOSTABLE MENSTRUAL PAD FROM WATER HYACINTH

by

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A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Sustainability Studies
August 2022

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ACKNOWLEDGEMENTS

The *Eichhornia* pad project has received support and attention from several organizations in the San Marcos, TX area of which I would like to give thanks. This includes the San Marcos River Foundation, Plum Creek Watershed Partnership, KXAN Austin – an NPR affiliate, The University Star, The Meadows Center, Paddling with Style, TedxTexasState, and the Texas State Sustainability Office. Through building relationships with these entities, awareness of the need for this product and the need to remove invasive species from the environment has increased. Through relationships and partnerships with these organizations, the health and biodiversity of the San Marcos River was promoted, and I had the honor to engage with some very intelligent environmental specialists and advocates.

I want to give special thanks to Virginia Parker for teaching me how to properly remove invasive aquatic species from the river and to Holly Orr for allowing me to use her canoes. Thank you to Dr. Christina Lopez for your academic partnership and for helping me remove invasive species within the San Marcos River and Plum Creek. I want to give a big thanks to Dr. Kimberly Meitzin for teaching me that the introduction of invasive species is among the top five threats to biodiversity. That lesson has guided my thesis research and it sparked my interest in communicating the need to upcycle invasive species. I am very grateful for the TedxTexasStateUniversity team for the opportunity to share my idea with the Texas State and San Marcos community. I would like to give a special thanks to Mark Paz for helping me create a great speech and for offering me mentorship and friendship throughout the process. I would like to give thanks to Sustainability Coordinator, Emma Parsley, and the Office of Sustainability for their volunteerism with invasive species removal and for the interest in my research.

I would like to thank my primary advisor, Dr. Gwendolyn Hustvedt, for her support and understanding throughout the process of completing this thesis study. Your understanding and patience towards me helped me overcome many obstacles throughout the process of thesis writing. Thank you for your formatting suggestions and encouragement. Thank you to Dr. Tina Cade and Dr. Colleen Myles for your support and guidance. I would also like to thank Dr. Catherine Hawkins for offering her mentorship throughout my time in graduate school and to Dr. Sangchul Hwang for his initial support in the project.

I would also like to express my gratitude to my parents, Kimberlye Olden, William Olden, and Jeffrey Vogel for backing me up and being excited for my research. Thank you, dad, for your help with my project and for teaching me skills I will use throughout my professional career. Thank you for being my number one fan in all the activities I get to be a part of. Mom and Coach, thank you for your current and continued support of me in my academic, career, and social endeavors. I would also like to thank my brother, Steven Vogel, for his guidance and care towards me throughout my time in graduate school.

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ABSTRACT

The water hyacinth (*Eichhornia crassipes)*, exhibits unique qualities that can be harnessed to create a product that promotes social equality: a compostable menstrual pad. Two countries, India and the United States share similarities in that *Eichhornia*, one of the world's most notorious invasive plant species, is a threat to the environment and economy in both places, and each country has thousands of individuals who live the effects of period poverty. Using *Eichhornia* as a resource promotes ecological stability, the economy, and society, and can benefit both India and the United States from the impacts of inadequate sanitation and period poverty.

This paper explores the potential of *Eichhornia* to be used as a resource when making value added goods. An in-depth analysis of sanitation insecurity will be provided, along with the social and environmental effects of poor sanitation, and the effects of period poverty. Following the analysis of the effects of poor sanitation and period poverty, recommendations are made on how to fabricate a menstrual pad utilizing the fibers of *Eichhornia*. The layers of a western-style menstrual pad will be deconstructed, and the distinct function of each layer will be explained. *Eichhornia* exhibits physiological characteristics that suit it for application in each layer of a menstrual pad.

Using *Eichhornia* to fabricate a compostable menstrual pad is just one example of how we can create value added products from invasive species that benefit people and the planet.

1. INTRODUCTION

Invasive plant species can be used to address social, environmental, and economic issues. One such plant, the water hyacinth (*Eichhornia*), exhibits unique talents that can be harnessed to create a product that promotes social equality. People who menstruate around the globe can be disadvantaged in comparison to their non-menstruating counterparts, especially in contexts with poor sanitation, a lack of resources to properly manage menstruation, and in areas where the cost of conventional sanitary pads is either subjectively or objectively high. A sanitary pad that addresses the concerns of price, availability, and cleanliness can be found through utilization of *Eichhornia*. We can use invasive species to address social issues. We can use *Eichhornia* to address issues of sanitation, gender equity, and period poverty.

According to Pavov et al. (2009), invasive species are indigenous or nonindigenous species that spread to different environments, with or without the influence of humans, and produce a significant change to the structure, composition, or processes of their environment or negatively affect economics. Fitting this description, like other invasive aquatic plant species, *Eichhornia* can cause decreases in overall biodiversity, generally increase turbidity, organic matter, and nitrogen levels, and decrease water and oxygen levels (Gallardo, Clavero, Sánchez et al. 2016). Invasive species pose severe economic impacts through the process of their removal and from the effect they have on farming, irrigation, navigation, and water consumption. It has been estimated that the global economic impact of invasive species over the last 50 years is a minimum of $1.288 trillion in damages (Zenni, Essl, García-Berthou et al. 2021). As the prevalence of invasive species increases, the monetary damage induced will also increase. The impacts of biological invasions span across geographical, social, and economical contexts. The prevalence of invasive aquatic species is becoming more overwhelming simultaneously with the Earth's natural resources dwindling. Humans need to utilize invasives species and take advantage of their ability to persist in harsh environments.

1.1 Upcycling Invasive Species

The removal of invasive species promotes society by supporting the growth of native plants and animals, which then positively affects the human population. We can change our perception of invasive plant species. One side of the stance views them as a threat to biodiversity, which is true, however, widening our scope when studying and managing invasive species would allow us to view them as a resource that has multiple positive impacts.Perhaps environmental problems caused by humans, such as the biological invasion of invasive species all over the globe, can be mitigated whilst mitigating social issues. Using invasive plants as a resource can potentially be a holistic solution to socioenvironmental issues.

Sanitation issues and period poverty can be addressed by an unlikely hero, *Eichhornia*. This plant has invaded the entire globe (Patel 2020) but can be utilized in a potential solution to global social, environmental, and health issues.

1.2 Aim of Study

The purpose of this study is to address sanitation issues regarding solid waste management and period poverty and promote ecological stability by providing recommendations on the advancement of creating a biodegradable or compostable sanitary pad from the invasive aquatic plant, *Eichhornia*. The environmental and economic impacts of *Eichhornia* will be discussed broadly and in specific cases within the United States and India. Both countries have been invaded prolifically by *Eichhornia* and have issues concerning sanitation and period poverty, though they are experienced differently in each country. The connection of *Eichhornia* to sanitation issues will be thoroughly discussed, as will the underlying factors that impeded progress towards the reduction of poverty through improvements in sanitation.

This study will provide a description of the area where *Eichhornia* was removed, the San Marcos River, along with a biological description of *Eichhornia* including its origins, how it spread to many parts of the globe, and the environmental and economic issues that it causes. The methods of control used to mitigate its growth around the globe will be examined and its potential upcycling applications. Around the world, many inventive uses for invasive aquatic flora have been identified and tested. In examining the potential applications of invasive species, perhaps their extraction will occur more often as their potential commodifiable applications and uses are identified. Lastly, this study will provide recommendations for the development of a compostable menstrual pad made from *Eichhornia*.

Fabricating a sanitary pad from the harmful *Eichhornia* addresses environmental, economic, and social problems. This study aims to build a foundation of research and recommendations for use in fabricating pad prototypes sourced from the fibers of *Eichhornia*. This study supports the advancement of knowledge on potential upcycling applications of invasive plant species found within the San Marcos River that are also prevalent around the globe.

This project was funded by the Ingram School of Engineering at Texas State University in San Marcos, Texas. The environmental engineering lab and the equipment used to process and prepare *Eichhornia* for experimentation were generously provided by the Ingram School of Engineering's Environmental Engineering Department.

2. LITERATURE REVIEW

Water hyacinth, *Eichhornia crassipes,* within the family Ponterederiaceac, is considered one of the world's worst weeds. The invasive pest grows prolifically in many parts of the globe; much scientific literature has focused on *Eichhornia* infestations in Africa, India, and the United States. This global traveler has several names: water lily, water weed, beautiful blue devil, among others (Holm et al 1977). Although *Eichhornia* is called by different names depending on the location, those who have witnessed the impact of the *Eichhornia* can agree that it is a pest that needs to be removed from non-native regions. In many areas around the globe, *Eichhornia* is an ecological and economic nuisance resulting in billions of dollars spent on its control annually and millions deducted from individual country or state annual net benefit.

This perennial aquatic pest homogenizes rivers, streams, lakes, and ponds as it becomes the dominant vegetation after its introduction into an area. *Eichhornia* can be found within the tropics and subtropics (Holm et al. 1977) but can also be found in areas that do not become too cold. Areas with high boating traffic or a propensity to have ornamental plants, such as *Eichhornia*, in private ponds are likely to encourage its spread. Its ability to duplicate with one seed, stem, or root allows it to be one of the most productive plants in the world. Its high growth rate is also cause for concern. A biological description will be provided for *Eichhornia* along with a background of how the weed has spread from its native region to many parts of the globe. How the plant reproduces and the effects it has on ecological communities will also be discussed in the following paragraph. Lastly, its impacts in India and the US will be covered thoroughly along with the biological, mechanical, chemical, and manual control tactics used to mitigate its growth.

Biology and reproduction of *Eichhornia*

Considered one of the world's worst weeds (Holm et al. 1977), this perennial, free floating aquatic plant is a major threat to native species. In deeper water, swarms of *Eichhornia* act as a platform for biota to reside on and can grow on top of itself in layers until it reaches the river bottom. In rare occasions in shallower water, it may root to the ground (Benton, James, and Rouse 1978). It can grow up to three feet in height, with stems comprising most of the plant length. The buoyant stems, or petioles, cause the plant to float on the surface thus limiting the amount of sunlight reaching below and inhibiting photosynthesis of underlying flora. The cellulose fibers within the petioles retain and transport water from the roots of the plant to the leaves, or laminas, and flower. The leaves are cordate and act as a sail to allow the plant to travel along streams and spread out as it catches the wind. Flowers are lilac to a light purple.

Once a flower withers, a mass of seed capsules is retained at the tip of the withered flower's stem. The glossy leaves in a rosette, or circular, form vary in size depending on the age of the plant. The root system grows out of nodes both horizontally and vertically. The horizontal roots, or stolons (much like a stem), connect mother plants to daughter plants, causing the surface area to increase exponentially through fragmentation. Each feathery vertical root is comprised of many tips that aid in the plant's ability to absorb nutrients and water rapidly. It has been observed that the vertical roots of the *Eichhornia* vary in coloration. Most commonly the roots are a faded black color, but other times the roots appear as a shade of indigo. The purpose of the alteration in color has not yet been discovered, however. *Eichhornia* can maximize in density of up to 2,000,000 plants per hectare and can weigh between 270-400 metric tons/hectare (Holm et al. 1977). Once an area becomes completely invaded by *Eichhornia*, navigation and recreational use of the area is nearly impossible. The anatomy of *Eichhornia* (Figure 1) predisposes it to be harmful within every body of water it habituates.

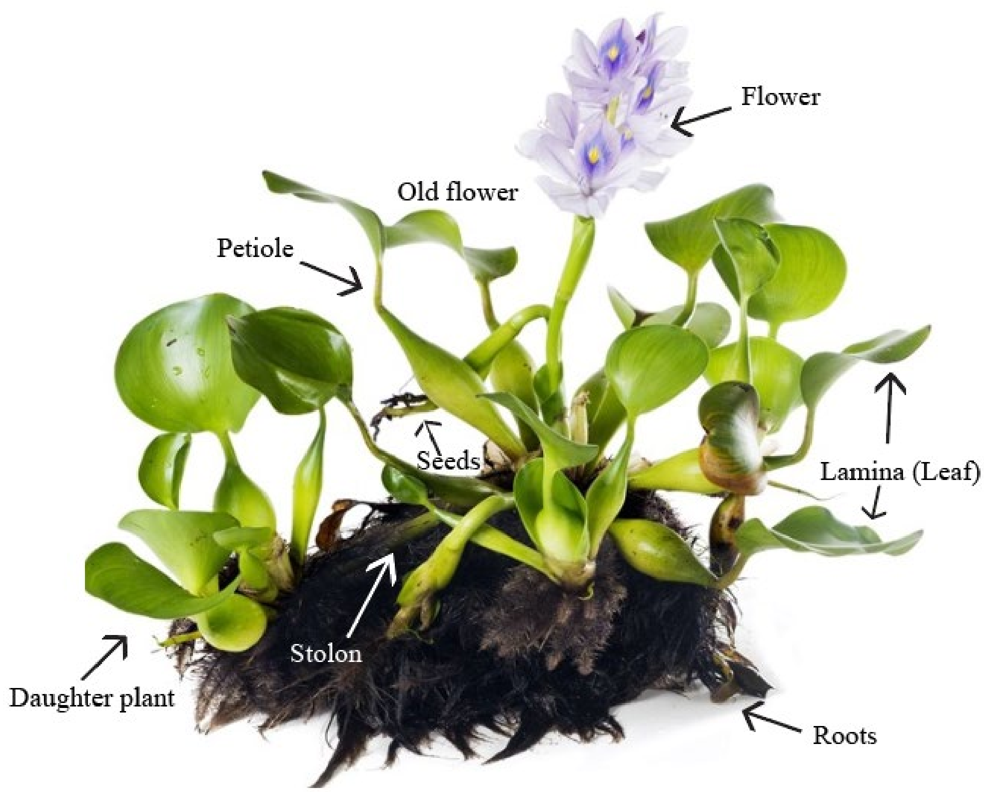


Figure 1: *Eichhornia* anatomy

Origin

Eichhornia is native to the Amazon River basin of South America. Its original introduction into the United States (US) is disputed. Some articles state *Eichhornia* was introduced to the US in 1884 at the Cotton States Exposition in New Orleans, Louisiana while others report evidence of it as a cultivated plant used as a landscape and greenhouse exotic after the Civil War (Penfound and Earle 1948). While at the Cotton States Exhibition, *Eichhornia* was admired for its beauty and ability to grow under almost any circumstances. After the Exhibition, it was cultivated in ponds and gardens for aesthetics and eventually spread through nearby streams (Klorer 1909). Reports of *Eichhornia* in Florida began in 1890 (Webber 1897) and the plant spread to California by the early 1900s (Johnson 1920). The attendees of the Exhibition were gifted *Eichhornia*, and some can infer that the Exposition was the key event that led the weed being anthropogenically dispersed to many states within the US.

In India, the earliest reported date of *Eichhornia* was at the end of the 18th century. According to Menon (2013), Lady Hastings, the wife of Warren Hastings who was the first British Governor-General, brought *Eichhornia* to India to be used as an ornamental. The precise location of where the weed was placed is not clear, however accounts report *Eichhornia* first being introduced into West Bengal. Today, *Eichhornia* has covered over 200,000 hectares of water in India (Jayanth 1988). Its beauty has led to the plant being intentionally dispersed to 80 countries within the last 100 years (Jafari 2010). The geographical extent of the plant is bounded by temperature; within the northern regions of the globe, temperatures become too cold for *Eichhornia* to grow. Once brought into an area, this productive plant will regenerate quickly and soon become predominant in the waterways. Today, in some places, the plant is still admired for its beauty and is cultivated intentionally. In short, its origins as a beautiful lawn ornament have led to it becoming one of the worst weeds globally.

Reproduction

Eichhornia thrives in freshwater bodies with a temperature ranging from 70-80 degrees Fahrenheit and has a doubling time of just 2 weeks. The quick growth rate combined with its' perennial nature is extremely harmful to the ecological health of many aquatic ecosystems. During flood events, it travels along streams and reproduces once it becomes stationary either by the flood subsiding or the roots connecting to a stationary object such as the river edge. After 26 days of growth, *Eichhornia* begins flowering and produces seeds. Once the seeds are released, they sink to the river bottom and can remain viable for up to 15 years (Benton, James, and Rouse 1978). The lengthy viability of the seeds increases the difficulty of fully eradicating *Eichhornia*. If the seeds are unremoved, a new colony will emerge, and the process will begin again. The seeds can also be spread through epizoochory as they stick to the legs of birds. Seeds will sprout in as short as 3 days and begin to produce leaves in 10. Petioles form and give the plant buoyancy along the surface, putting it in a competitive position against native plants to undergo photosynthesis. *Eichhornia* flowers can be pollinated, however most reproduction of the weed occurs asexually or as flowers wilt and self-pollination occurs. Seeds are released from the withering flower within a few weeks.

From mother plants, daughter plants grow out of durable stolons. It has been observed that 2 parent plants can asexually produce 30 offspring in just 23 days and 1,200 in 4 months (Holm et al. 1997). Several *Eichhornia* can grow in a small area, so when colonies do form, the area becomes very densely populated by the invasive weed.

See Figure 2 for a visual on the thick mats formed by *Eichhornia* that inhibits sunlight from reaching underlying flora and acts a floating habitat for small organisms, such as mosquitoes.

Figure 2: Thick mat formed by *Eichhornia*.

This image was captured along the San Marcos River at Scull's Crossing outside of Martindale, TX.

Effects on river ecology

Trophic interactions are altered during *Eichhornia* growing season in warmer months (usually March- September) in areas that experience colder temperatures during fall and winter. In areas that stay warm, the plant will grow year-round. Aquatic vegetation is placed under stress because of the limited sunlight levels, which then negatively impacts consumers that feed on producers. Not only do mats of *Eichhornia* growth inhibit sunlight from reaching underlying plants, *Eichhornia* also reduces oxygen levels in aquatic bodies. This is harmful to the fish population as it limits the areas they can spawn.

Due to its inclination to form thick mats on the surface, mosquitoes and other pests habituate on top of *Eichhornia* and lay eggs at water level. *Eichhornia* holds the eggs at the surface and acts as a shelter for the larvae, keeping them from being eaten by small fish and amphibians (Benton, James, and Rouse 1978). The major effects on fish populations are dependent on the original food-web structure exhibited by the ecosystem. In most cases, however, due to *Eichhornia* decreasing phytoplankton production, the dissolved oxygen level will also decrease, thus limiting the areas of fish population growth.

It has been observed that herbivorous fish do not feed *Eichhornia*. It does not hold much protein, so it is not a good choice for fish consumption (Villamagna and Murphy 2010). Because the food source of small fish is limited by the plant, larger predatory fish are also affected. On a small sized pond, it has been observed that 5% surface area coverage by *Eichhornia* has no effect on the fish population, but once coverage reaches 10-25%, the population of fish decreases (McVea and Boyd 1975). *Eichhornia* also lowers the water table with an evapotranspiration rate ranging from 2-8 times greater than a free surface (Holm et al. 1977, Van der Weert, and Kamerling 1974). For an organism to survive against the competition posed by the *Eichhornia*, it must be equally, or more, perennial and persistent. Often, the only plants to survive alongside *Eichhornia* along the surface are also invasives, such as elephant ear (see Appendix: Figure 24), water lettuce (see Appendix: Figure 23), and alligator weed (see Appendix: Figure 22). Observation on the San Marcos River (SMR) from San Marcos to Martindale, TX, reveal that elephant ear, water lettuce, and *Eichhornia* densely populate the same areas. Water lettuce grows along the outside of *Eichhornia*, and elephant ear will grow along the shore, between *Eichhornia* and the bank of the river. Figure 3 shows the growth of elephant ear, water lettuce, and *Eichhornia* within proximity of each other.

It is common for several invasive aquatic species to occupy the same areas. Alligator weed, a highly invasive aquatic weed first discovered in the US in the late 1800s, faced competition with *Eichhornia* as they grew in similar environments. *Eichhornia* slowed the spread of alligator weed through competition, however alligator weed began to grow more prolifically once chemical control began to be employed during the 1940s. Alligator weed exhibited a resistance to the chemicals that were applied to both alligator weed and *Eichhornia*, thus tipping the scale in favor of alligator weed. The weed then began spreading to areas that were once completely occupied by

Eichhornia (Tanveer et al. 2018). Today, however, *Eichhornia* appears to be a dominate species within the SMR.

Figure 3: Elephant Ear, *Eichhornia*, and water lettuce growth within the San Marcos River. Water lettuce, a lighter green, grows within the upper-middle portion of the figure. *Eichhornia* can be seen along the bottom of the figure towards the right corner. Elephant ear is along the left side of the figure. The dark green leaves can be spotted within the grasses growing along the bank of the river. This figure was captured along the SMR at Scull's Crossing outside of Martindale, TX.

Control and management of *Eichhornia*

Several tactics for controlling *Eichhornia* growth have been used around the globe including biological, chemical, mechanical, and manual control. The method used is dependent on the desired outcome. Each method is used ultimately to remove *Eichhornia* from waterbodies, however some methods are used to ensure *Eichhornia* stays intact so the weed can be made into a variety of applications. Control methods and applications of *Eichhornia* used around the globe will be discussed, along with the pros and cons of each method.

Biological control, primarily with the usage of weevils (Deloach and Cordo 1983; Jayanth 1988), has proven to be one of the most successful methods of controlling the growth of *Eichhornia* (Charudattan, Labrada, Center et al. 1995). Other species that have been used to mitigate *Eichhornia* growth are the Colombian ramshorn apple snail, mites, paddy grasshopper (Sankaran et al. 1966), Water Hyacinth moth, and fungal pathogens (Cilliers 1991). This method is suggested to be the most economical and sustainable control tactic of the plant (Cilliers 1991; Harley, Julien, and Wright 1996; Hill and Coetzee 2008; Jones 2009), but the effectiveness of biological control, primarily through the introduction of insects, in terms of long-term impacts on aquatic biodiversity and health are unsettled (Center, Dray, Jubinsky et al. 1999). Non-target species are vulnerable as new control agents, typically insects, are brought into areas overgrown with *Eichhornia*. Non-target plant species can unintentionally be reduced as well as generalist species (introduced to an area to mitigate the growth of a singular invasive plant) feeding on a wide range of unintended vegetation, which causes separate environmental concerns. Identification of biological control agents that solely feed on the desired invasive plant is difficult and often does not occur. With biological control agents, the start point of visible reduction in the growth of undesired vegetation can take years to occur (Schooler, Yeates, Wilson et al. 2007). Typically, an integrated approach using biological control and another form of control method is used to manage invasive aquatic weed growth.

Mechanical extraction is economically unfeasible in developing countries as equipment and maintenance can be cost intensive (Charudattan, Labrada, Center et al. 1995) and time consuming (Greenfield, Siemering, Andrews et al. 2007). However, mechanical extraction and shredding of *Eichhornia* has proven to increase water column nutrients (Greenfield, Siemering, Andrews et al. 2007) from the decomposing organic matter (Mangas-Ramirez and Elias-Gutierrez 2004). According to Mara (1976), mechanical control offers lower environmental impact compared to chemical and biological control as the harvesting of *Eichhornia* mechanically does not harm fish and causes an immediate beneficial effect to water quality. But other studies indicate that mechanical control of *Eichhornia* leads to a decrease in dissolved oxygen and an increase in toxins like ammonia (Mangas-Ramirez and Elias-Gutierrez 2004). These changes could lead to a reduction in native biota. The variability of information reported on the mechanical removal of *Eichhornia* could suggest it is an unfavorable strategy in terms of overall sustainable aquatic ecosystem conservation.

Chemical control has several of its own detrimental environmental risks, so this method is, in some cases, ecologically unacceptable (Jones 2009) due to the harmful effects of herbicides to the aquatic environment (Charudattan, Labrada, Center et al. 1995). Chemical control commonly includes the continuous application of herbicides to isolated groups of invasive aquatic plants (Netherland, Getsinger and Stubbs 2005). Usage of herbicides is extensive in places like Florida, where *Eichhornia* management can cost millions annually (Netherland, Getsinger and Stubbs 2005). When *Eichhornia* coverage is very large, the plant is more likely to persist after the application of herbicides. Like biological control agents, chemical applications are not site specific. The chemical applied to communities of *Eichhornia* can negatively alter the growth of unintended plant species. Chemical control is less expensive than mechanical control, however, some herbicides cause long-term environmental impacts. Herbicides can disrupt the hydrological system along with human health as the chemicals can enter groundwater sources (Rapid and Responsive Evidence Partnership 2021). Application of herbicides needs to be very specific as other biota can be affected.

Manual control is more time exhaustive and laborious (Jones 2009), however the *Eichhornia* can still be yielded with as much precision as mechanical control. When focusing on harvesting invasive aquatic weeds, hand weeding is most effective to ensure the entire plant is being removed (Hofstra, Clayton, Champion et al. 2018). *Eichhornia* can become heavy as it becomes saturated with water. Removal of the *Eichhornia* can be physically tiring as several of the plants are connected to each other and can weigh several pounds. Energy exerted during the removal process often does not appear equal to the number of *Eichhornia* removed from the water. Also, many organisms harbor within the roots of the weed and on top of the plant. It is important to ensure native microorganisms are not removed along with the *Eichhornia*.

When *Eichhornia* is being used to create products or in other applications, manual and mechanical control are utilized most often. Mechanical control will yield the most *Eichhornia*, so this method is best to use when large amounts of the weed are needed for the desired product. Manual control is useful in ensuring the entirety of the plant is removed, providing more portions of the weed to be used to fabricate products.

2.1 *Eichhornia* in India and the United States

Eichhornia is a pest to aquatic ecosystems worldwide. Developing and developed countries both struggle with this invasive plant, with its extent of impacts varying depending on the predominant source of income for the country or area. In a developing country, such as India, *Eichhornia* is a major threat in that it clogs freshwater bodies, thus limiting the area for agricultural and farming use, recreation, and its high evapotranspiration rate poses problems as the majority of water consumed in India comes from surface water sources. In a developed country, such as the United States (US), *Eichhornia* presents similar concerns. However, state economies that are more dependent on freshwater use and river tourism are more impacted by the plant than states that are not. Both countries are put under stress by the prolific nature of this invasive plant. That being said, countries could instead benefit from this invasive plant. India and the US have similarities in that *Eichhornia* is a threat to the environment and economy in both places, and each country has similar social issues occurring that could be addressed through the utilization of the *Eichhornia*.

India

Eichhornia is the most prolific aquatic weed in India (Jayanth 1988). The weed inhibits economic growth by disrupting tourism, fishing, hydroelectricity production, and navigation within waterways. It is also a major threat in maintaining the health of aquatic ecosystems and biodiversity. It disrupts farming, specifically rice cultivation. During the wet season, irrigation water flushes *Eichhornia* into rice fields and must be removed by farmers (Ghosh 2010).

In many parts of the country, *Eichhornia* is utilized in a multitude of applications in upcycling methods. Eichhornia's natural absorptive properties and propensity to expand in surface area exponentially makes it a very useful and abundant resource to create products from. In a developing country such as India, it poses as an agent for frugal economic growth in areas that do not have access to expensive production machinery or removal equipment. Also, in being so prolific and readily accessible, frugally made *Eichhornia* products can be easily duplicated and fabricated on an individual level, not just exclusively through mass production. *Eichhornia* exists dichotomously as a super pest and as a potential solution for many world problems including hunger, poverty, access to medicine, shelter, and clothing (Monsod 1979). Upcycling invasive *Eichhornia* is a holistic solution to environmental, economic, and (depending on the end product) social and health issues.

United States

Since its introduction in the United States, *Eichhornia* has been observed along the West Coast (primarily CA), along the East Coast, the Northeast, and in the South. The states under the most stress from *Eichhornia* are Florida, Alabama, Louisiana, and Texas (USGS 2021). *Eichhornia* is a serious economic nuisance, resulting in up to millions of dollars spent annually on its removal. In Florida, it has been estimated that controlling three major invasive plants (*Eichhornia*, water lettuce, and hydrilla) results in an annual net benefit of about $60 million. A break in control results in an estimated loss of about $19 million annually (Adams and Lee 2007) which could incrementally increase annually should the populations of the invasive plants disperse. Much like Florida, Texas is affected economically by *Eichhornia*. An economic impact assessment has not been undergone to estimate the annual costs of *Eichhornia* control or the fiscal impact of its presence, however the House Committee on Culture, Recreation, and Tourism (2013) has reported the recreational impacts of *Eichhornia* to the Texas Legislature and has stated that TX generally has 6,000-14,000 acres covered with *Eichhornia* during its growing season. According to Texas Parks and Wildlife, intensive control of *Eichhornia* is estimated to cost around $45 million annually but since 2016, only $3.2 million has been spent on control annually. The recreational and environmental impacts of *Eichhornia* are widely understood, however the uses and positive applications of *Eichhornia* are much less discussed in TX. Most literature on the weed from academic sources and governmental organizations solely discuss the best methods of control and its problematic nature.

Just as *Eichhornia* is a serious issue in both India and the US, issues surrounding sanitation, managing menstruation, and period poverty persist in these countries as well. Upcycling invasive species, specifically *Eichhornia*, acts as a unique opportunity to create potential solutions for social benefit. Along with addressing social issues, the removal of the plant or other invasives supports the environment. *Eichhornia* is an unlikely resource that can be used to address social, economic, and environmental concerns.

Using invasive plant species to make menstrual products is a solution to many environmental problems. The removal of invasive aquatic species is beneficial as it supports biodiversity, increases water and dissolved oxygen levels, and increases navigability of waterways. As the products are made from an abundant resource, the cost of the products should be relatively low compared to plastic-based products. The removal of invasives will continue as a market for cheap alternatives will always be present. The biodegradability of natural products eliminates the residual environmental effects of managing menstruation. By not using and harmful additives, pollutants will not enter waterways or landfills during the degradation process. Also, if a used pad exhibits compostability, a secondary byproduct can be made from the sanitary pads post usage. Compost with the addition of *Eichhornia* produces a useful product for agriculturalists, botanists, and other users of compost (Montoya, Waliczek, and Abbott 2013). Replacing plastic-based, single-use, ecologically harmful products with a cheap, environmentally friendly product upcycled from invasive plant material supports the three pillars of sustainability: economy, society, and environment.

2.2 Gender and Sanitation

Gender discrimination in academia has led to the unequal representation of women. Gender bias and the androcentrism entrenched within scholarly research on health has recently undergone fragmentation as awareness of the institutionalized patriarchal influence has grown. Males and females do not share the same experience so men cannot serve as a gold standard to base sanitation and health on. Should an androcentric view be used to address sanitation, females will continue to be disproportionately affected by poor sanitation (Vogel, Hwang, and Hwang 2022). The presence of women in decision making groups needs to increase, especially in the case of water and sanitation as women are impacted differently by the lack of these resources and, in developing countries, rely on these resources to engage in their primary responsibility within the household. At the International Conference on Water and the Environment in 1992, Principle 3 recognizes the important role of women as users and providers of water and as protectors of the physical environment (Brewster et al. 2007) by stating, "Women play a central part in the provision, management and safeguarding of water" (Eales 2012). Including women in the decision-making process on issues, specifically those involving water and sanitation, will generate solutions that address more individuals. Traditionally, decisions are made by a singular category of people thus tailoring to that single category. Without the inclusion of women, a cycle of neglect will continue (Mahon and Fernandes 2010) and the reduction of poverty through improvements in sanitation will stagnate.

Historically, improvements on awareness of menstrual health are a slow process. When women's health is at the focal point, it has been in regard to sexual and reproductive health, such as family planning, sexually transmitted diseases, birth control, and contraceptives (Sommer and Sahin 2013; Vogel, Hwang, and Hwang 2022). An androcentric approach to women's health such as this succumbs to the limiting parameters of traditional gender roles (Vogel, Hwang, and Hwang 2022). According to Levinson (1976), "sexist belief systems foster social control by blaming the victim, create a gender-related invalid through labeling, and keep women from achieving educationally and occupationally" (428).

Women are more affected by the lack of adequate sanitary conditions (Vogel, Hwang, and Hwang 2022) compared to males. Lacking proper sanitation is an "affliction of the vulnerable and marginalized," and women, "more often than men," experience the health impacts of inadequate sanitation (COHRE 2008) and safe water (Brewster et al. 2007; Vogel, Hwang, and Hwang 2022). As a gendered affliction, inadequate sanitation affects women, like men, regarding hygienic maintenance and methods of defecation, however women undergo additional obstructions to maintain their hygiene (Vogel, Hwang, and Hwang 2022). and attempts to hygienically manage oneself are made more difficult during menstruation.

Attention to menstrual health increased when the gender gap in education was given global recognition and action (Sommer, Hirsch, Nathanson et al. 2015). It then realized that if girls were able to attend school just as much as boys, the gender gap would shrink. Also, women with more years of education have fewer and healthier children. There are cultural, economic, and personal safety related barriers that impede women from gaining their right to education. Making schools more girl-friendly and helping them overcome the health barriers that impede them from attending school as often as they can needs to be addressed (Hawken 2017). The role gender plays in the quality of sanitation a person receives is irrefutable. Females experiencing period poverty are more likely to experience health issues and attend school less than those who have access to resources and education.

Period poverty

Period poverty is a branch within the arena of sanitation and public health. It is defined as the absence of FHPs, education on menstruation and menstrual health, sanitary facilities, and waste management (Sánchez and Rodriguez 2019). It is a symptom of androcentric influence and capitalistic market systems overshadowing menstrual hygiene management (MHM). Millions of people menstruate daily, and the availability of resources varies depending on their location, economic situation, and culture. Around one-fourth of the menstruating population claim they do not have access to the resources they need in order to manage menstruation (Sommer and Mason 2021). As femininity is entangled with a diminutive societal perception, menstruation is often perceived more as a limiting social phenomenon rather than a naturally occurring physiological process. The effects of period poverty include higher rates of absenteeism of females in work and school, health issues such as urinary and reproductive tract infections, and social exclusion. The ability to manage menstruation in a clean and dignified manner is a right all people who menstruate must have (Vogel, Hwang, and Hwang 2022) to achieve equity among all people. Addressing menstrual equity and fairness in the availability and affordability of FHPs supports overall equality and human rights.

Period poverty in the United States

In the US, public schools are bound by law to provide FHPs (categorizing them as essential as toilet paper) for students, but through personal experience, menstrual products are often not made available or are not consistently replenished. Female students in the US can experience difficulty managing menstruation due to stigmas and embarrassment (Brooks-Gunn and Ruble 1982; Havens and Swenson 1986; Stubbs 2008; Stubbs, Rierdan, and Koff 1989). As legislation passed that made FHPs mandatory to be provided for free, the social and psychological factors that influence menstruation management and health (Cotropia 2019) were not fully addressed. Within the carceral system, menstrual products have only been free since 2018 (Sánchez and Rodriguez 2019). Instead of being seen as an essential like toilet paper or hand towels, the necessity of FHPs has been taken advantage of and females reap the burden of gendered marketing and excessive pricing.

Low-income women who cannot afford menstrual products rely on the free products provided by community organizations or non-profits that are sometimes less absorbent. A study on low-income women from 10 different community groups in Missouri found that, two-thirds could not afford menstrual products and one-third resorted to using cloths, rags, or tissue paper to absorb their discharge. The inability of these women to afford menstrual products led them to use material that is far less effective and that could have led to leakages and embarrassment (Kuhlmann, Bergquist, Danjoint et al. 2019; Sommer and Mason 2021). Especially in low-income areas, the inaccessibility to menstrual products, specifically their unaffordability, leads women to have to use other materials to suffice that are not as effective, clean, or discrete. Vulnerable populations, specifically those that are homeless, face increased difficulties in managing menstruation.

A study found that the difficulties homeless women faced while menstruating were that products were inconsistently or insufficiently provided at locations that give them for free and accessibility among the homeless population varied depending on if they lived in a shelter or not (in this study it is disclosed that the Department for Homeless Services shelters are required to provide free menstrual products in New York) (Gruer, Hopper, Smith et al. 2021). Women that live in shelters are more likely to have access to menstrual products and sanitary facilities than those living on the streets. A 2021 survey on teenagers in the US revealed that over a quarter had difficulty affording FHPs and over half wore menstrual products longer than the recommended time (Elflein 2021). In the US, period poverty is not marked by a lack of resources per se, but the inability to afford those resources. The commodification of FHPs has unenabled many people to be able to manage their menstruation in the most clean and healthful way due to unaffordability.

Period poverty in India

The issue of period poverty in India differs from that in the US as the issue is engulfed in several fragmented social, economic, political, and cultural systems. Free Periods, a campaign that advocates for period products in schools, argues that period poverty denies girls the right to their education and governments should be required to provide free products for them. In the case of India especially, solving period poverty requires a solution beyond providing cheap FHPs. When products are being provided, providers also needs to ensure that women know how to use them. Increasing knowledge regarding how to use FHPs, on menstruation itself, and proper methods of disposal must be addressed (Cousins 2020). Providing these goods and teaching how to use them would help greatly, however the entrenchment of distaste, impurity, and a sense of weakness toward femininity requires a change in how women are treated and how menstruation is viewed by society. The sense of impurity connected to menstruation is common among Muslim and Hindu people. In both Muslim and Hindu religions, women are unable to visit holy places or touch religious texts while they are menstruating (Garg et al. 2001). The social impact of this compulsory physiological occurrence spans across several spheres of a woman's life. Menopause, puberty, menstruation, and pregnancy are sometimes viewed as conditions contributing to a woman's frailty (Levinson 1976). In recent decades, however, the direction of research has positioned women in an empowered and equitable position simply as humans who deserve human rights (Vogel, Hwang, and Hwang 2022).

2.3 Menstrual Hygiene Management

According to Critchley, Babayev, Bulun et al. (2020), menstruation is the cyclical bleeding process that occurs between menarche, the first period a menstruating individual experiences, and menopause. This natural process has no cultural or geographic bounds, yet as sociological influences vary depending on the location of the menstruator, stigmas and perceptions associated with menstruation vary from being accepted and understood to the indicator of impurity and shame (Vogel, Hwang, and Hwang 2022). The ability to manage menstruation is dependent upon physical limitations of the menstruator, the resources an individual has access to, and the cultural beliefs held within their location (Vogel, Hwang, and Hwang 2022).

Menstrual hygiene management (MHM) is an issue of social justice within the realm of public health (Sommer et al. 2015; Vogel, Hwang, and Hwang 2022). Menstrual health includes accessibility of menstrual products, safe, hygienic bathroom facilities, and requires accurate information being relayed and taught on menstruation. Inadequate MHM is a precursor to reproductive tract infections (Das, Baker, Dutta et al. 2015). Menstrual health has joined the global agenda (Critchley, Babayev, Bulun et al. 2020) with focus set on women's access to sanitary products, education, toilets, and clean water in developing countries (Vogel, Hwang, and Hwang 2022).

The cost of feminine hygiene products (FHPs) is often too expensive for some women so alternative products are used. In India, sanitary products cost between 5-12 rupees (0.08-0.20 USD) (Rodriguez and Gralki 2019), but as 800 million people live on less than 1.90 USD per day in the country, commercial FHPs are unobtainable (Vogel, Hwang, and Hwang 2022). Personal care or sanitary products suggested for women are often more expensive than products suggested for men. Making products targeting women more expensive than those for men demotes gender inequality as the economic burden of womanhood increases and "bolsters essentialist thinking regarding gender" (Duesterhaus, Grauerholz, Weichsel et al. 2011; Vogel, Hwang, and Hwang 2022). Laws have been set in place that protect women from workplace discrimination, but women are not protected from gender discrimination within the marketplace (Ayres 2001). Products that are targeted for women can be full of toxins and harmful to several bodily systems.

Health issues associated with feminine hygiene products

Plastic-based FHPs pose many health issues that are not shared as public information. FHPs are considered medical devices so potentially harmful materials and the detrimental effects they can have to users is not, by law, mandatory to be disclosed (Women's Voices for the Earth 2014). The array of toxic ingredients used in FHPs are dangerous no matter the location of exposure. Harmful chemicals used in popular menstrual products can take affect via dermal exposure or vaginal exposure. Mucous membranes in the vaginal system absorb chemicals rapidly without a metabolization process causing a higher rate of exposure to harmful chemicals than what was intended by manufacturing companies (Nicole 2014).

The addition of carcinogenic and system disrupting ingredients is a direct attack to the bodies of females. Fordism and the desire to make products in the cheapest and most rapid form has cast a shadow over women's health. Volatile organic compounds

(VOCs), furans, phthalates, and dioxins are commonly used in plastic-based FHPs (Cardoso, Clark, Rivers et al. 2019; Scranton 2013; Weuve, Hauser, Calafat et al. 2010) as inexpensive means to increase comfort, flexibility, absorbability, and economic profit.

To increase structural integrity and flexibility of products, major corporations that sell women's sanitary products use plasticizers, such as polyethylene and polypropylene, that contain harmful phthalates. Phthalates are known endocrine disruptors. Studies indicate a connection between phthalate exposure and preterm birth (Cardoso, Clark, Rivers et al. 2019), ovulation disorders (Weuve, Hauser, Calafat et al. 2010), and precocious puberty (Kim, Lee, Kim et al. 2019). Women's Voices of the Earth (2014) reports the presence VOCs, styrene, chloroethane, chloroform, acetone, and chloromethane in popular scented FHPs. Some VOCs are known to cause reproductive damage, cancer, and damage the kidney and liver (Lin, Ding, Meza-Wilson et al. 2020). Dioxins and furons, such as polychlorinated dibenzofurans and polychlorinated dibenzo-p-dioxins, are byproducts of bleaching treatments (Shin and Ahn 2007).

Many companies bleach plastic-based FHPs to make them appear whiter and more sterile upon purchasing. Exposure of furons and dioxins can cause endometrial cancer, endometriosis, and uterine leiomyomata (Shin and Ahn 2007). Several synthetic materials, such as viscose rayon, are used as an absorbency enhancer and are mixed in with cotton in plastic-based tampons. The rate of Toxic Shock Syndrome (TSS), a life-threatening disease caused by bacterial toxins, increased when companies started prolifically using these synthetics as an ingredient in tampons. After the detection of synthetics and their ties to increased rates of TSS, several synthetic chemicals were banned from being added into tampons, excluding viscose rayon (Nicole 2014). Although viscose rayon is known to cause TSS, its usage is still prevalent by major companies. See Table 1 for toxins found in some FHPs and their related health effects.

Table 1:Toxins found in some feminine hygiene products and related health effects.

Pads	Toxins: Furans, dioxins, fragrance chemicals, pesticide residue, adhesives. Related health effects: cancer, endocrine disruption, harm to reproductive system, rashes
Tampons	Toxins: Furans, dioxins, chlorine, fragrance chemicals, pesticide residue. Related health effects: cancer, rashes, Toxic Shock Syndrome, harm to reproductive system, endocrine disruption
Douche	Toxins: Fragrance chemicals, Octoxynol-9 (spermicide) Related health effects: cervical cancer, STDs, HIV transmission, birth complications, preterm birth, yeast infections, infertility, pelvic inflammatory disease, bacterial vaginosis
Feminine Wipes	Toxins: Parabens, methylisothiazolinone, methylchloroisothiazolinone, quaternium-15, fragrance chemicals Related health effects: endocrine disruption, cancer, rashes
Feminine Wash	Toxins: Parabens, methylisothiazolinone, methylchloroisothiazolinone, harmful dyes Related health effects: asthma, rashes, endocrine disruption

Information retrieved from Women's Voices for the Earth (2014).

Solid waste generated from single-use menstrual products

Not only do these toxic ingredients harm the user, single-use, plastic-based FHPs are harmful to the environment during production and post usage as they are discarded into landfills or flushed into wastewater streams. It has been estimated that in the US alone, approximately 12 billion pads and 7 million tampons are discarded yearly (Dillon 2017). During the menstruating lifecycle, it is estimated that a single menstruator will use between 5-15 thousand pads and tampons (Borunda 2019). Super absorbent polymers (SAPs), commonly derived from petroleum, are used as an addition in menstrual pads to increase absorbency but are the leading contributor in global warming potential in diaper manufacturing. The emissions associated with developing and extracting the materials needed in menstrual product production have not been quantified. Raw material acquisition, processing, followed by packing and distribution have yet to be quantified as well.

Along with harmful chemicals, plastic-based FHPs release microplastics into the environment once discarded. Single-use products made of primarily plastic take centuries to fully degrade. Microplastics (< 5.0mm) threaten people and aquatic environments as they enter waterways. Microplastics bioaccumulate in humans and aquatic fauna and can cause negative health effects (Rezania et al. 2015). Eliminating the addition of plastics in FHPs and having better methods of waste disposal will decrease the amount of microplastics and harmful chemical accumulation in water systems and bioaccumulation.

Disposal of FHPs is usually done in waste receptacles and sent to landfills, but these products are also flushed down the toilet, resulting in plumbing issues or complications at wastewater treatment plants. Flushing of products that should be disposed of in a landfill is a contributor to infrastructural and environmental problems such as water quality issues and plastic pollution (Alda-Vidal, Browne, and Hoolohan 2020). Disposable sanitary pads and tampons pose the biggest environmental impacts compared to other menstrual products (Hait and Powers 2019), such as menstrual cups or period panties, based on the material sourcing, production, and packaging of the products. The waste generated from plastic-based FHPs has severe ecological and health implications (Achuthan, Muthupalani, Kolil et al. 2021; Tudu 2021), but could be mitigated by using reusable or biodegradable alternatives. In being sourced from natural places, especially when said sources are invasive and unwelcome flora, pricing of biodegradable menstrual products should be comparatively inexpensive. Several FHPs made from naturally derived material such as jute, banana, bamboo, and *Eichhornia* fibers have been fabricated, however attention to these products needs to increase and research on these sources should be emphasized.

In 2020, over 57 million women in the US used single-use sanitary pads and napkins (Statista Research Department 2021). The switch to reusable or biodegradable alternatives is more common in the US than in India, however waste is still rapidly generated from single-use tampons and sanitary pads. In India, sanitary napkins are the most common product used during menstruation (Bhor and Ponkshe 2018). However, cultural stigmas and social taboos circulating around femininity and menstruation cause women to be reluctant in using hygienic methods to manage menstruation. Some women use ash, soil, or dried leaves to absorb discharge (Bhor and Ponkshe 2018) because of product unavailability and the misconceptions held on menstruation that limit women's ability to manage menstruation in a dignified manner. According to WaterAid India (2007), of the 336 million women that menstruate in India, over 120 million use sanitary pads. Assuming each woman will use around 8 pads per cycle, it is estimated that 1 billion sanitary pads are used monthly and 12 billion are used annually. In rural areas where solid waste disposal systems are not set in place, women often discard sanitary pads in open fields, or in bodies of water such as lakes, streams, and ponds. As discussed earlier, the degradation process of plastic-based sanitary products takes millions of years. The accumulation of sanitary pads in fields and bodies of water increases the sanitation problem currently faced in India. As most people rely on surface water for daily usage, contamination from inadequate sanitation services causes severe health problems. It has been recorded that 70% of surface water in India is polluted (ADRI 2017) and is unfit for consumption.

There is a need for menstrual technology that both promotes the social mobility of women (and all menstruators) and does not pose any environmental harm pre and post usage. A compostable menstrual pad made from the fibers of an invasive plant material would address both of these needs while also supporting ecological stability as its production requires the removal of a harmful aquatic flora.

3. METHODOLOGY: PRODUCT DEVELOPMENT AND EXPERIMENTATION

This project identifies some of the best practices for developing the most efficient and stable pad prototype using the invasive *Eichhornia* from the San Marcos River. Utilizing product development methods focused on prototyping, recommendations will be made on how to harness the physiological characteristics of *Eichhornia* to best suit the requirements of each layer of a menstrual pad. Along with providing recommendation on how to use *Eichhornia* for each layer of a pad, a cross comparison with the layers of a conventional (petroleum based) menstrual pad will be provided. See Figure 19 for a visualization of a deconstructed conventional pad and *Eichhornia* pad. Experimentation with the fibers of *Eichhornia* was used to test the fibers capabilities in being used as an additional in hydrogels (Figure 12) and how the fibers would perform in combination with raw cotton to suit the requirements of a menstrual pad layer (Figure 18).

Following the recommendations made in this study, future developments must test the structural integrity, absorptive ability, flexibility, and biodegradability to identify which prototype and fabrication methods to use in order to create the most effective menstrual pad. Using multi-criteria analysis, the pad prototype that reigns overall could be identified. Sectors of the multi-criteria analysis could be based on several benchmarks that are important for menstrual pad users. This includes absorbency, durability, biodegradability, flexibility, and cost. The best overall prototype will be identified along with indication of which prototype is the best within each category. From there, this foundational research can be expanded by producing more of the best overall pad prototype and testing its efficacy on human subjects or through focus groups.

Sustainable solutions are those that incorporate the well-being of all in decision-making. They also include taking actions that benefit the present population without jeopardizing the ability of future generations to have access to those same resources. Utilizing *Eichhornia* to make a pad that promotes women's equality, fairness in pricing, and environmental health will aid in mitigating the effects of period poverty, promote healthy MHM, could increase the level of sanitation in many areas, and promotes sustainability. All countries, regardless of economic prowess, could benefit from an inexpensive and compostable alternative to plastic-based, single use sanitary pads. From the upcycled *Eichhornia* pad's beginning to end, it has the potential to benefit all people and the planet.

This project was funded by the Ingram School of Engineering at Texas State University in San Marcos, Texas. University vehicles, the environmental engineering lab, and the equipment used to fiberize and test the ability of *Eichhornia* to suit the requirements of each layer of a western-style menstrual pad were graciously supplied by the Ingram School of Engineering's Environmental Engineering Department. Team members for this project included three Civil Engineering undergraduate students, a graduate student (me), and an Environmental Engineering professor. Under the supervision of the Environmental Engineering professor, the team of undergraduate researchers and I extracted, prepared, and assessed Eichhornia for the purpose of this study.

Manual control tactics were employed to remove *Eichhornia.* Once removed, the plant was transported to the lab to be cleaned. The *Eichhornia* fibers were shaped and prepared using standard paper making methods, various machinery was tested to see which was the most efficient at fiberizing the dried petioles, then several formulations of hydrogels were created to see which would be most useful in application within the absorbent core of a menstrual pad.

3.1 Location of Study: The San Marcos River

The San Marcos River (SMR) (Figure 4) is a persistent place, being the longest continually habituated area in North America. Today, the SMR provides recreational and educational opportunities to the community and tourists. The constant flow of cool (22 ºC) spring-fed water also attracts thousands of travelers each year. River tourism accounts for a large portion of the City of San Marcos' annual economic growth. According to TXP, Inc. (2017), river tourism contributes over $180,000 (in sales tax) every year to the City. As the population of Hays County increases, river tourism remains steady and fiscally supports this growth. The cleanliness and serviceability of the river are important as it is a source of income for the area. The City of San Marcos, the San Marcos River Foundation (SMRF), Texas Stream Team, The Eyes of the San Marcos River, Free the San Marcos River, Edwards Aquifer Habitat Conservation Program, along with several Texas State University organizations are devoted to preserving the SMR as a resource for the community and habitat for many aquatic species. Common activities across the organizations are litter removal, invasive species management, and water quality monitoring.

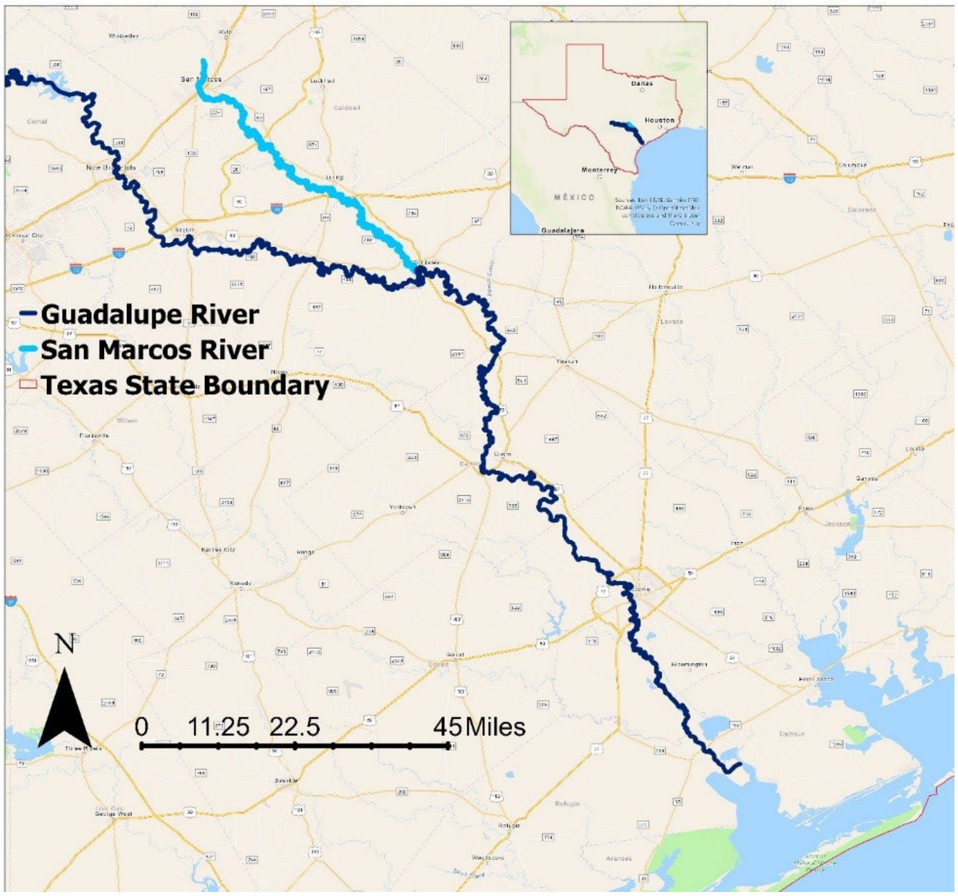


Figure 4: The San Marcos River. Image created by Raihan Jamil.

The SMR originates from 200 artesian spring openings from the Edwards Aquifer below Spring Lake in San Marcos, TX. The upper 3.8 miles of the river is a vital habitat to many threatened and endangered species including the Texas blind salamander, San Marcos Salamander, Texas wild rice, San Marcos fountain darter, and San Marcos gambusia (Bartlett 1995, SMPR 2021). It is one of the most biologically diverse aquatic habitats in the southern United States. As the population of San Marcos and surrounding areas continues to grow, ensuring the protection of the river and the many aquatic species it harbors is vital. Once it has risen from the springs in San Marcos, the SMR flows 75 miles until it converges with the Guadalupe River near Gonzalez, TX. The SMR harbors many native species but is also the site of several invasive plants such as hydrilla, *Eichhornia*, water lettuce, alligator weed, and elephant ear (Table 2).

Table 2: Characteristics of *Eichhornia crassipes*, *Hydrilla verticillate* (hydrilla), *Alternanthera philoxeroides* (alligator weed), *Pistia stratiotes* (water lettuce), and *Colocasia esculenta* (elephant ear).

	Invasive aquatic plants found within the San Marcos River				
Characteristics	*Eichhornia*	Hydrilla	Alligator weed	Water lettuce	Elephant ear (corms)
Cellulose (%) Hemicellulose (%) Lignin (%)	25 33 10[10]	28 32 40[11]	29 32 24[12]	35 26 11[13]	13 70 -[14]
Nutrients	Na, Mg, P, K, & Ca[2,4,5] Vitamin A & protein[4] Fe, Zn, Cu, & Mn[5]	Vitamins B-1, B-2, B-3, B-5, B-6 & B12[6] Ca, Mg, K, Fe, Zn, & beta carotene[6]	K & P[1] Pb & Zn[7]	K, Ca, Mg, P, Na, Fe, Mn, Cu, & Zn[3] Vitamins A, B & C[9]	Vitamins A, B, C & E[8] Mg, Ca, Fe, K, niacin, riboflavin[8]

Optimum pH	5.0-7.5[15]	Wide range[16]	4.8-7.7[17]	6.5-7[18]	5.5-7.0[19]
Optimum Temp. (°F)	54-95[15]	68-81[16]	50-98[17]	70-80[18]	69-82[20]

Sources: [1] Dujing et al. 2008, [2] Gunnarsson & Peterson 2007, [3] Rodriguez et al. 2000, [4] Monsod 1979, [5] Mako et al. 2011, [6] Pal & Nimse 2006, [7] Ye et al. 2011, [8] Pereira et al. 2020, [9] Aasim et al. 2013, [10] Istirokhatun et al. 2015, [11] Promdee et al. 2021, [12] Bhattacharjee & Biswas 2018, [13] Madeno˘glu et al. 2018, [14] Hussain et al. 1984, [15] Pond Informer 2019, [16] Sea Grant Pennsylvania, [17] CABI, [18] Puisis 2021, [19] Beaulieu 2021, [20] Andrews 2021

3.2 Removal and Utilization of *Eichhornia*

Eichhornia is very prevalent within the SMR and is harmful to native flora and fauna. Working closely with the San Marcos River Foundation (SMRF), *Eichhornia* was removed along the river by a research team comprised of three Civil Engineering undergraduate research students, an Environmental Engineering professor, and a Sustainability Studies graduate researcher (myself). The research team actively worked to promote the health of aquatic ecosystems through the removal invasive aquatic species from the SMR and research their potential upcycling opportunities. The primary plant of interest to the research team is *Eichhornia* as this plant possesses a unique combination of physiological characteristics that makes the plant highly absorptive and malleable upon fiberization.

Locations of *Eichhornia* sample collection

In two-person canoes provided by Paddle With Style, the research team travelled along the SMR to find hotspots of *Eichhornia* growth from Rio Vista Park in San Marcos to the Luling Dam in Luling, TX. Specific locations of WH extraction are Spring Lake in San Marcos (29.8913° N, 97.9319° W), Cummings Dam (29.8561° N, 97.9059° W), Sculls Crossing (29.3952354° N, 98.1272303° W), Cottonseed Run in Martindale, TX (29.8537131° N, 97.8668235° W), and Staples Dam (29.78332° N, 97.83111° W) in Staples, TX. See Figure 5 for the locations of *Eichhornia* extraction along the SMR from San Marcos to Luling.

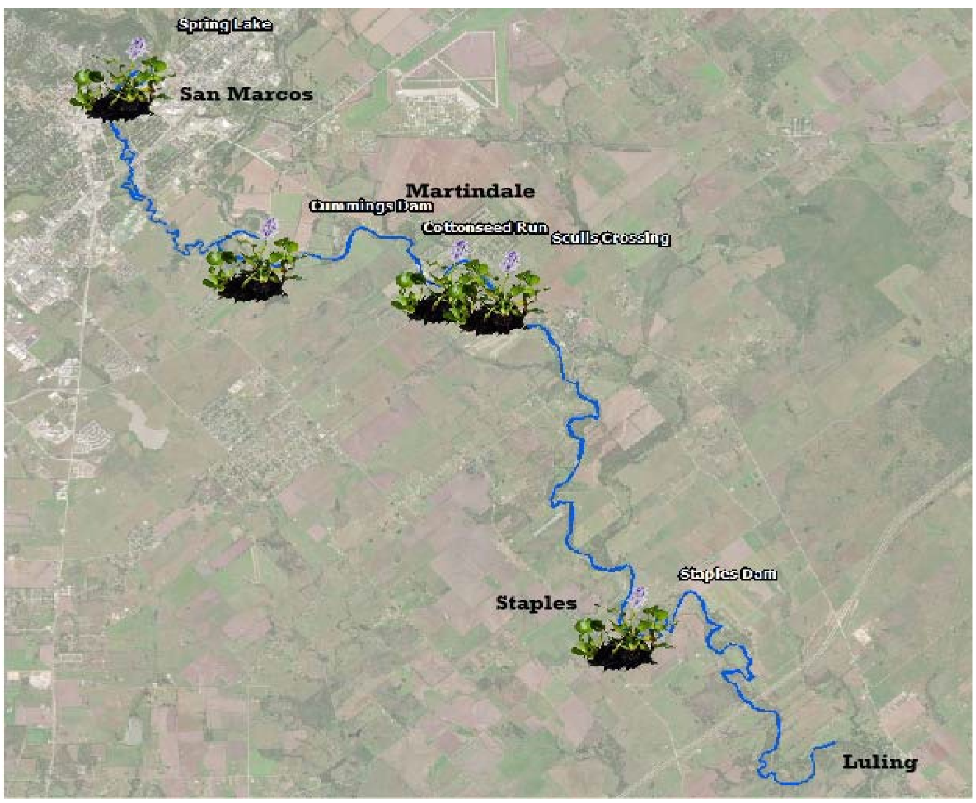


Figure 5: *Eichhornia* extraction points along the San Marcos River.

4. RESULTS: *EICHHORNIA* REMOVAL/PREPARATION AND EXPERIMENTAL PROTOTYPING PREPARATION

The team paddled within a range of 1-3 miles up and downstream of the drop off point to collect *Eichhornia* along with removing litter, water lettuce, and alligator weed. Trips to extract *Eichhornia* took place up to 1-2 times every 2 weeks during the months June-July, 1-2 times a month from August-September, then once a month from October-December to accommodate to the seasonality of the invasive plant. Time on the water canoeing to locations of *Eichhornia* growth and employing manual extraction would last 1.5-2.5 hours each trip.

4.1 Plant Removal

Using gloved hands, the team employed manual control tactics to remove *Eichhornia*. Along with manual removal, small hoes called 'Smurfs' were used to reach *Eichhornia* that were too far from the canoe to reach by hand. Individual *Eichhornia* were lifted from the surface of the water and shaken off to allow native microorganisms, such as aquatic macroinvertebrates and larvae and nymphs of mayflies, caddisflies, and dragonflies, to fall back into the water that were residing within the root system of the weed. Once the majority of water dripped from the weed and most microorganisms had been manually shaken off, the *Eichhornia* were placed in large laundry baskets inside the canoes. After being placed in the laundry baskets, water within the root system of *Eichhornia* continues to drain out and microorganisms that weren't fully shaken off float along the floor of the canoe.

Once the team paddled back to the drop off location, the canoes are flipped over so river water and floating microorganisms can flow back into the river. While employing manual control to remove *Eichhornia* along the SMR in areas that are densely populated, four individuals can remove five 56-gallon trash bags of *Eichhornia* in about one hour. Each 56-gallon bag of *Eichhornia* varies in weight, typically 15-30lbs, depending on how full it is packed, the size of *Eichhornia* removed, and how saturated with water the stolons are. Once placed in the trash bags, they are transported to the Environmental Engineering lab to be processed. Processing the *Eichhornia* includes the removal of the root system, thorough cleaning using water and rags, additional removal of remaining microorganisms, and drying out *Eichhornia* using either an industrial drying oven, drying in the sun, or through isolation in a fume hood.

4.2 Fiber Preparation

Once in the lab, one-by-one *Eichhornia* is removed from the trash bags to remove the roots and begin cleaning the plant. Scissors are used to cut the roots from the stem of the plant. Upon observation, the root systems can vary in length and weight. If the location of collection was comparatively shallower or dirtier to other sections of the river, the root system will be full of soil and solids. The roots can have a very pungent odor depending on the depth of water the *Eichhornia* was extracted from. Once the roots are removed, they are placed in a bucket and set aside from the bag containing the collected *Eichhornia*. To clean the stem and leaves, a large bucket is filled with water and the remaining *Eichhornia* is cleaned by hand by dipping it into the bucket and rubbing off dirt and particulates. Once cleaned, it is placed in a container to begin the drying process. Several *Eichhornia* stems can be placed in one container to be dried. Depending on the drying method used, the containers that hold the cleaned *Eichhornia* are either plastic (for air drying or drying under a fume hood), or metal (for use in the industrial sized dying oven). The methods of drying in either sunlight (Jafari 2010), fume hood, or drying oven (Guna et al. 2017; Ibrahim, Ammar, Soylak et al. 2012), are successful in allowing access to the cellulosic material of *Eichhornia* and drying out the plant so it can be used in various applications.

The process of root removal and cleaning can take between 1-3 hours depending on the quantity of *Eichhornia* extracted and the number of research team members working together. The amount of time needed to dry out *Eichhornia* depended on the drying method used. Using the drying oven requires the least amount of time as the temperature inside can be controlled. With this method, however, the plant can become overcooked and turn from a lively green color as it was upon extraction into a light brown color. The drying oven produces dried *Eichhornia* that appear to be cooked rather than the fume hood or sunlight drying which does not result in baked *Eichhornia*. The color turns into a light green or whitish color when using the fume hood and sunlight drying methods. Once dried, the fiberization process begins. This is undergone by placing the dried *Eichhornia* stems and leaves inside of a blender, Nutribullet, or Industrial grinder. Several types of blenders have been tested and each result in different sized dried *Eichhornia* fibers.

Three types of blenders were used to produce fibers from the dried *Eichhornia*. The size of fibers produced differs with each blender.

The Store-bought blender (Figure 6) is much like the regular blenders purchased for home use. The cost can vary between 20-50 USD. The fibers produced from the store-bought blender are larger and flakey in appearance (Figure 7).

Figure 6: Store-bought blender.

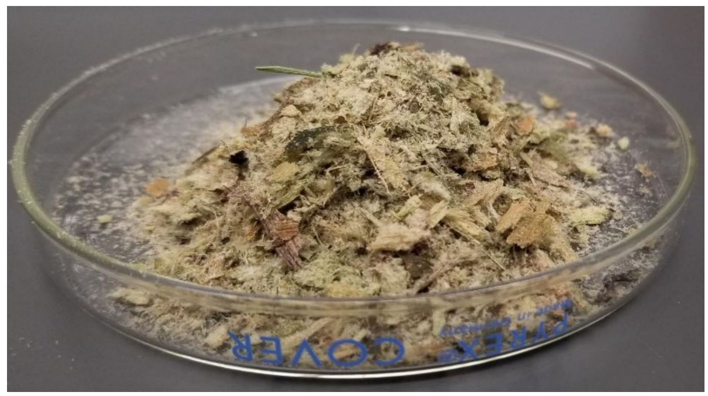


Figure 7: Fibers generated from Store-bought blender

The Nutribullet (Figure 8) can be purchased in most grocery stores and costs between 40-85 USD depending on which Nutribullet is purchased and the number of accessories that come with it. The fibers produced by the Nutribullet are similar to those created by the store-bought blender.

Figure 8: Nutribullet

The High-speed multifunction industrial grinder (Figure 10) can be purchased between 140-170 dollars. The industrial grinder produces very fine fibers in the form of a powder (Figure 9). The industrial grinder generates fibers of the smallest size compared to the other blenders; however, it is the most expensive of the three.

Figure 9: Goldenwall industrial grinder

Figure 10: Fibers produced from Goldenwall industrial grinder

The *Eichhornia* fibers generated from each blender can be used to fabricate compostable menstrual pads. The Store-bought blender and the Nutribullet are the more ideal options when finances and availability are concerns for those wanting to duplicate the pad making process. The Goldenwall Industrial Grinder produces the finest fibers, however, is the least accessible due to its cost and because it must be purchased online or requested in a special order.

4.3 Preparation of Hydrogels Using *Eichhornia*

Incorporating *Eichhornia* into the production of hydrogels requires modification of the quantity of chemicals used. To prepare hydrogels incorporating fiberized *Eichhornia* the following procedures were taken: a $CaCl^2$ (Calcium Chloride) solution was prepared by combining 22.2 grams of $CaCl^2$ and 400 mL of deionized water. The $CaCl^2$ solution was stirred at 400 rpm until the $CaCl^2$ dissolved in the deionized water. To make the *Eichhornia* hydrogels (Figure 12), 4 grams of sodium alginate, a polysaccharide extracted from algae commonly found in seaweed, and 2 grams of fiberized *Eichhornia* were incrementally added into a graduated cylinder with 200 mL of deionized water every 5 minutes. The deionized water was placed on a magnetic mixer at a rate of 150-400 rpm as the *Eichhornia* and sodium alginate were added into the solution. As *Eichhornia* and sodium alginate were added into the deionized water, the viscosity of the solution increased.

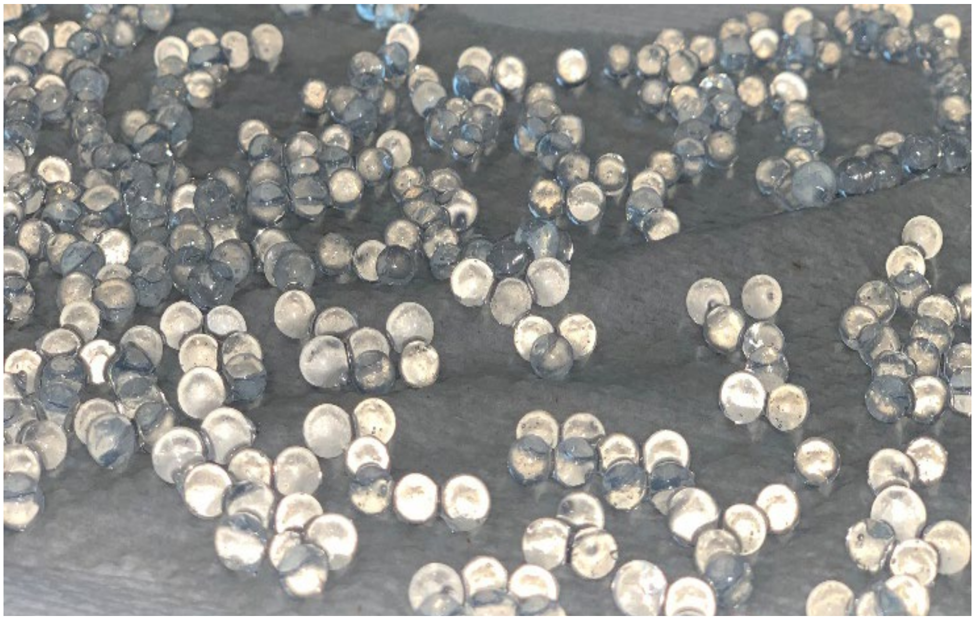


Figure 11: Hydrogels produced using sodium alginate


Figure 9: Hydrogels produced using *Eichhornia* fibers and sodium alginate

The rpm was modified within the range of 150-400 rpm to accommodate the addition of *Eichhornia* and sodium alginate so that the magnetic mixer stayed rotating. Once *Eichhornia* and sodium alginate were completely homogenized within the 200mL of deionized water, the resulting gelatinous solution was extracted using a syringe (Figure 13).

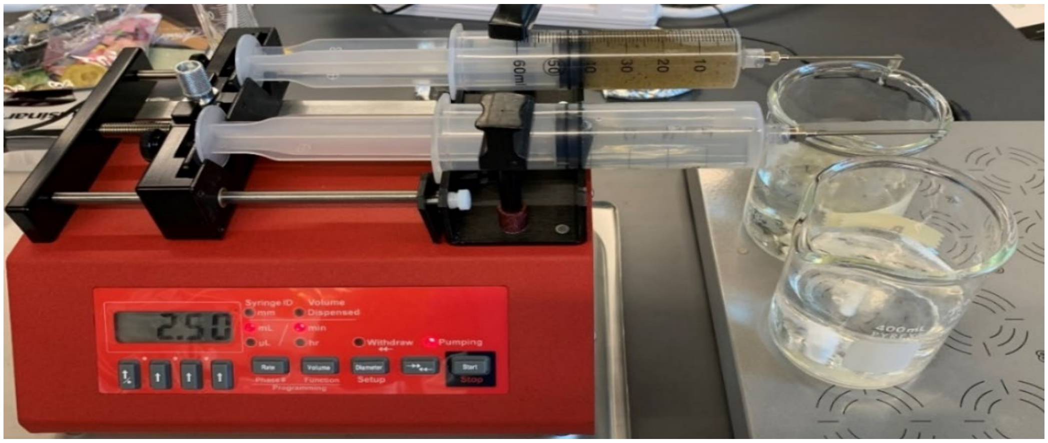


Figure 10: Mechanized syringes used to incrementally release the homogenized *Eichhornia* fibers and sodium alginate solution

Along with leaving the hydrogels in orb form, a mold (Figure 14) was created for the hydrogel to be set in to create the shape of the Absorbent core / SAP core. The homogoneous mixture of fiberized *Eichhornia* and sodium alginate solution was squirted into the 3D mold using a syringe. A $CaCl^2$ solution was poured into the bottom of the mold so that the homogenous mixture would begin forming into the shape of the core of a menstrual pad.

Figure 11: 3D mold with *Eichhornia* and sodium alginate hydrogel.

5. DISCUSSION: RECOMMENDATIONS FOR THE DEVELOPMENT OF AN *EICHHORNIA* MENSTRUAL PAD

Around the globe women undergo obstacles as they attempt to address menstruation in the most healthful manner possible. As discussed, women in both developing and developed countries must adapt to the resources available to them, the quality of sanitation within the regions they live, the cultural influences on how menstruation and femininity are perceived, and the social stigmas associated with menstruation. An accumulation of factors has made the necessity of a compostable menstrual pad apparent. A menstrual pad that does not contain harmful additives is paramount in supporting women's health and well-being. A deconstruction of a pad fabricated from *Eichhornia* fibers and a conventional pad using petroleum-based materials will be provided. The layer composition of both pads will be assessed and compared.

Figure 15 visualizes a conventional menstrual pad in deconstructed form. Each layer provides a specific function within the menstrual pad. The addition of harmful chemicals and plasticizers within conventional pads has improved their effectiveness and absorptive capabilities, however this has been done at the expense of the health of people who menstruate and the environment. Most conventional menstrual pad contain five layers: an emollient layer or top layer, an acquisition or transfer layer, an absorbent core or superabsorbent polymer (SAP) core, a bottom layer, and an adhesive layer. The primary functions of each layer of a menstrual pad will be discussed along with a description of the materials commonly used when fabricating a conventional menstrual pad.

As each layer of the conventional menstrual pad is deconstructed, recommendations will be made on how to utilize invasive plants, specifically *Eichhornia*, to fabricate the five layers of a compostable menstrual pad that could rival the effectiveness and absorbency of its conventional counterpart.

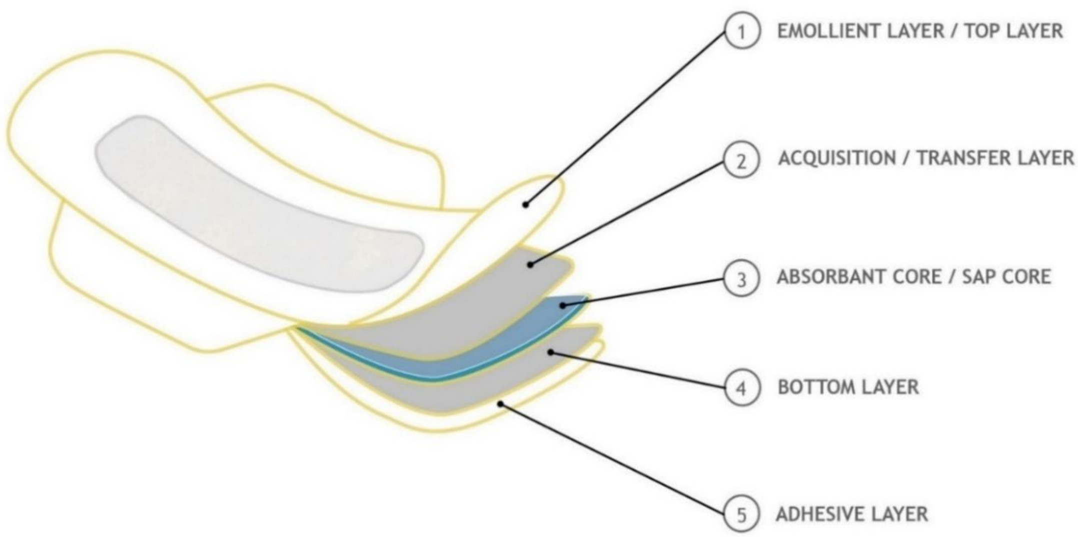


Figure 12: Deconstructed conventional pad
A deconstruction of a conventional menstrual pad. Each layer provides a specific function.

5.1 Emollient Layer / Top Layer

The purpose of the emollient layer / top layer is to capture fluids and allow them to seep through to the rest of the pad. An emollient is added to provide comfort and ensure the skin is not irritated from dermal contact with the surface of the pad. The emollient layer / top layer is highly permeable, allowing aqueous substances to seep through to the rest of the pad.

Conventional pads: Perforated fabric comprised of polyethylene or polypropylene fibers are used for the top layer. Petroleum-based emollients are used to ensure there is no discomfort to the skin (Woeller and Hochwalt 2015).

Eichhornia pad: The top sheet will be a combination of raw cotton fibers and fiberized *Eichhornia*. To ensure the cleanliness of both the *Eichhornia* and raw cotton (Figure 16), the materials should be disinfected. An emollient addition will not be included; however, a thin sheet of raw woven cotton will ensure dermal comfort is maintained and will pose close to no skin irritation.

Figure 13: Raw cotton

5.2 Acquisition / Transfer Layer

The function of the acquisition / transfer layer is to act as a distributor of liquids through the remaining layers of the pad. If liquids absorbed are only sent through one section of the pad, wetting or staining of the undergarment may result. The acquisition / transfer layer disperses liquids laterally throughout the absorbent layer / SAP core to ensure full coverage is maintained and the entire pad is being utilized.

Conventional pads: The Acquisition / transfer layer of a conventional pad is made using composite nonwovens that are either air bonded or thermally bonded (Kiron 2012). Nonwovens are typically films, fibers, or filaments entangled together using mechanical, thermal, or chemical bonding.

Eichhornia pad: The Acquisition / transfer layer of the *Eichhornia* pad can be made from raw cotton. The cotton can be separated a fluffed using a wire brush. Once the cotton is fluffy, it can be chopped into small pieces. The cotton pieces can then be mixed with water to form a form of pulp. The pulp can then be poured onto a sheet strainer and pressed into the desired shape. Once in the desired shape, the resulting cotton sheet must be dried to ensure it is solidified. Cotton acts as an imbibing agent within the compostable pad. Liquids that come in contact with cotton are absorbed throughout horizontally, thus dispersing liquids to remaining layers in the same fashion. The underlying Absorbent core / SAP core will come in contact with liquids spread-out through the layer, not all in one direction or point of contact.

5.3 Absorbent Core / SAP core

The Absorbent core / SAP core is the primary location of fluid containment. This area is the most absorptive layer but also provides flexibility.

Conventional pads: Synthetic material is commonly used as the Absorbent core / SAP core of conventional menstrual pads. The synthetic material used in conventional pads is often petroleum based.

Eichhornia pad: The Absorbent core / SAP core can be made from natural polymers derived from biological material such as sodium alginate and fiberized *Eichhornia*.

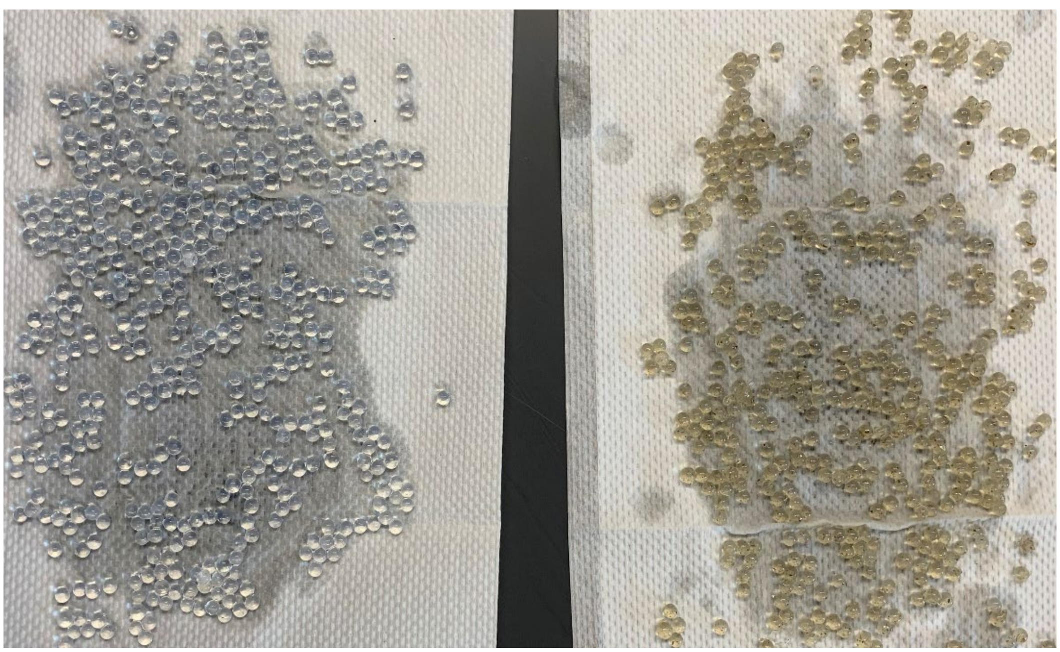


Figure 14: Sodium alginate hydrogels (left) and *Eichhornia* fibers and sodium alginate hydrogels (right).

5.4 Bottom Layer

The bottom layer acts as an impermeable barrier that inhibits liquids from seeping through. Impermeability must be maximized to ensure there are no leakages during the menstrual cycle. The bottom layer has negligible dermal contact. Studies indicate the materials used within the bottom layer of a menstrual pad have little to no skin exposure (Siddiqe 2019; Woeller and Hochwalt 2015).

Conventional pads: The impermeable bottom layer is made from a pigmented, low-density film based from polyethylene. Polyethylene, a polymer of ethylene, used today is primarily based from petroleum sources including propane, butane, and ethane (Ronca 2017).

Eichhornia pad: The bottom layer can be comprised of the same materials as the top layer: a mixture of raw cotton and fiberized *Eichhornia*. However, should the materials be the same for both the top and bottom layer, an impermeable layer must be added to the bottom layer so that it meets the requirement of impermeability. The high cellulose content of *Eichhornia* (Table 2), (25% cellulose, 33% hemicellulose, 10% lignin), gives it potential to be used to make a bioplastic (Anantachaisilp, Siripromsombut, Ruansoong et al. 2020). Following extraction of the cellulose by means of carboxymethylcellulose and NaOH and $NaClO^2$ treatment to remove the hemicellulose and lignin (Anantachaisilp, Siripromsombut, Ruansoong et al. 2020), cryocrushing (Mochochoko, Oluwafemi, Jumbam et al. 2013), or fiberization using a blender, the resulting *Eichhornia* material can be dissolved into water (Anantachaisilp, Siripromsombut, Ruansoong et al. 2020), or thoroughly mixed, then dried in a mold.

The addition of a plasticizer such as polyethylene glycol, a biodegradable compound approved by the US Food and Drug Administration, increases flexibility and performance as the bioplastic produced from WH has shown to be brittle (Anantachaisilp, Siripromsombut, Ruansoong et al. 2020). Alternatively, the cellulosic content of *Eichhornia* can be used to make polyhydroxybutyrate, a biodegradable polymer similar to that of polypropylene, and used as an addition to make bioplastic (Reddy, Reddy, and Gupta 2013). Corn starch can also act as a "leak-proof back sheet" impermeable layer in a compostable menstrual pad (Sareen 2021; Sparkle n.d). Elephant ear has also been used to produce biodegradable films which can be used to act as an impermeable bottom sheet below the bottom layer. Because elephant ear has a high starch content (Table 2), the invasive plant can be used to create a biodegradable film. Flexibility can be improved by incorporating glycerol, a compound commonly derived from plant material (Briones et al. 2015).

5.5 Adhesive Layer

The adhesive layer allows the menstrual pad to stick to the undergarments of the menstruator. The adhesive layer is identical in size with the body of the pad but includes two "wings" on the outside of the pad that fold around the crotch of undergarments.

Conventional pads: The material used in conventional pads to ensure the pad is fastened to the undergarments are hydrocarbon resins, polyolefinic or polyaromatic block copolymers, or mineral oil (Woeller and Hochwalt 2015). The adhesive layer does not come in direct dermal contact.

Eichhornia pad: To fasten the pad to undergarments while also promoting the compostability of the pad, the adhesive layer can be produced using products verified by the Biodegradable Products Institute (BPI). According to BASF (2019), BPI tests and verifies products under American Society for Testing and Materials (ASTM) standards to ensure their compostability. Developing compostable adhesives is difficult as the product must be broken down by microorganisms within 90 days of its discard. Within that time span, 90% of the adhesive must convert into a combination of CO2 and water vapor within a temperature range of 122º-140ºF (BASF 2019). With this in mind, ensuring ASTM standards are met and compostability is guaranteed, products endorsed by BPI will suffice for the *Eichhornia* pad. These products and corporations include Non-warp glue from Adhesive Products, Inc., LD Davis Industries, among several others (BPI n.d.). BPI endorses commercialized products from major corporations, however natural adhesives such as honey or soy protein isolate could be used as well.

Honey has been used in medical treatments and shows strong adhesive properties (Maghsoudi and Moradi 2015). Honey can be solidified and flattened into malleable strips to place at the base of the *Eichhornia* pad and provide adhesion to undergarments. Soy protein isolate has also been used as an adhesive in combination with rosin ester resin, an ester derived from trees, and has proven to rival the adhesion of commercial glue (Trinh 2012). The addition of rosin ester resin eliminates the need to add a petroleum-based synthetic material to increase adhesion, thus maintaining biodegradability and limiting the carbon footprint of the adhesive layer.

To maximize the frugality and duplicability of a compostable *Eichhornia* pad, the most readily available resources will be used, and fabrication must employ inexpensive equipment. Some processes of extracting the cellulose content from the stolon of *Eichhornia* involve experimental processes and acute scientific knowledge within the field of chemistry, biology, or hydrogel sciences. With this knowledge a successful product can be fabricated, however more frugal and adoptable methods can be used to reach a comparable result.

5.6 Single-layer *Eichhornia* Menstrual Pad

Another way to make a successful pad prototype using the fibers from *Eichhornia* is through the fabrication of a single-layer sanitary pad. The Jani Pad (Table 4) successfully utilizes *Eichhornia* to create a product like this. JaniPads are a combination of woven *Eichhornia* laminas (for absorbency) and Beeswax (for cohesion) (Roblin 2011). Following this basic structure, a single-layer menstrual pad (Figure 18) can be created in the same fashion as the Top Layer and the Bottom layer of the *Eichhornia* pad proposed above. A combination of raw cotton fibers and the fibers of *Eichhornia* can be mixed into water then poured onto a rectangular strainer so the water can be drained out. Once the rectangular sheet of cotton and *Eichhornia* is dry, it can be cut into a desired shape. This sheet can then be placed in the external pocket within the crotch region of some undergarments.

Figure 15: Single-layer *Eichhornia* menstrual pad

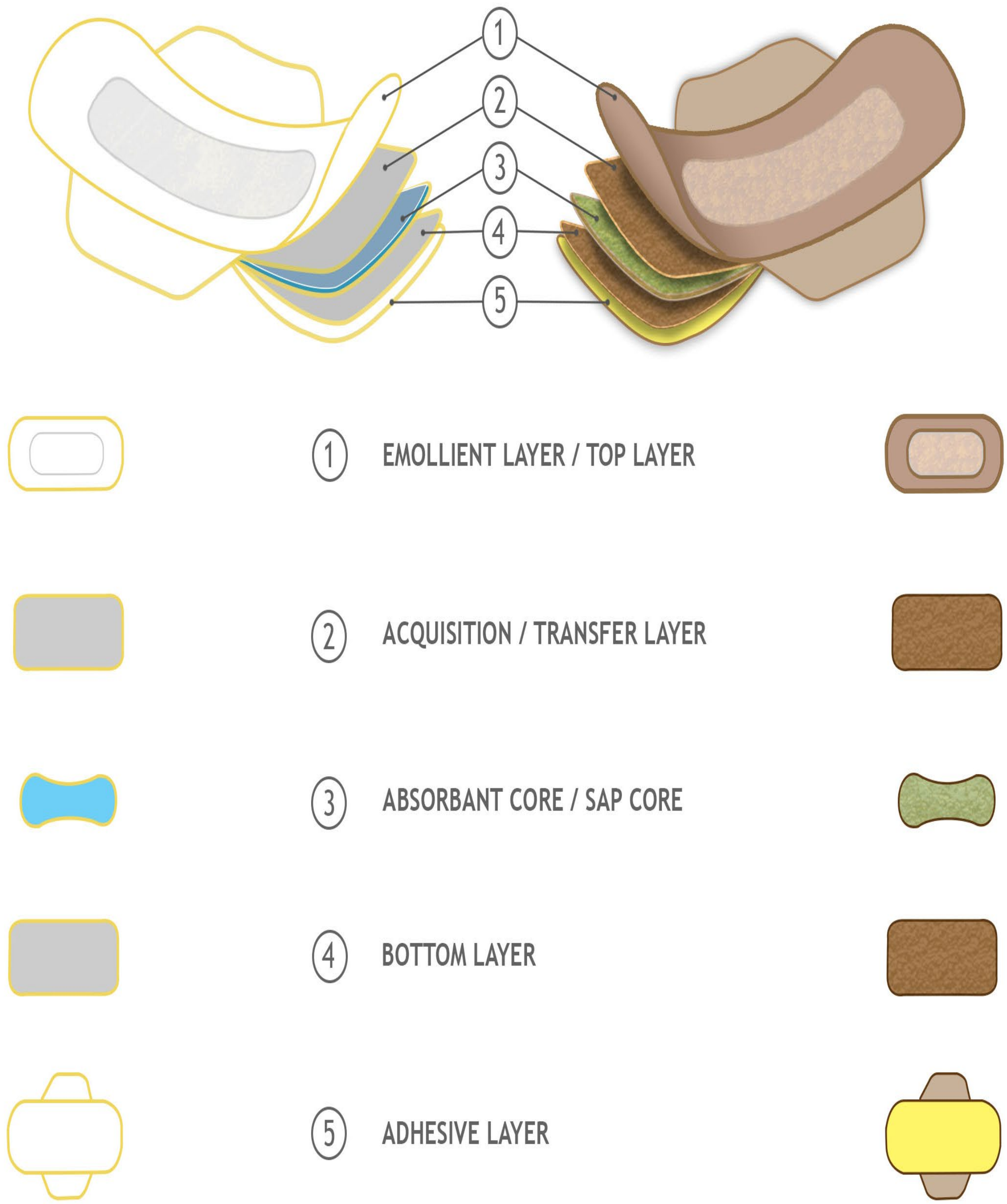


Figure 16: Conventional pad and *Eichhornia* pad

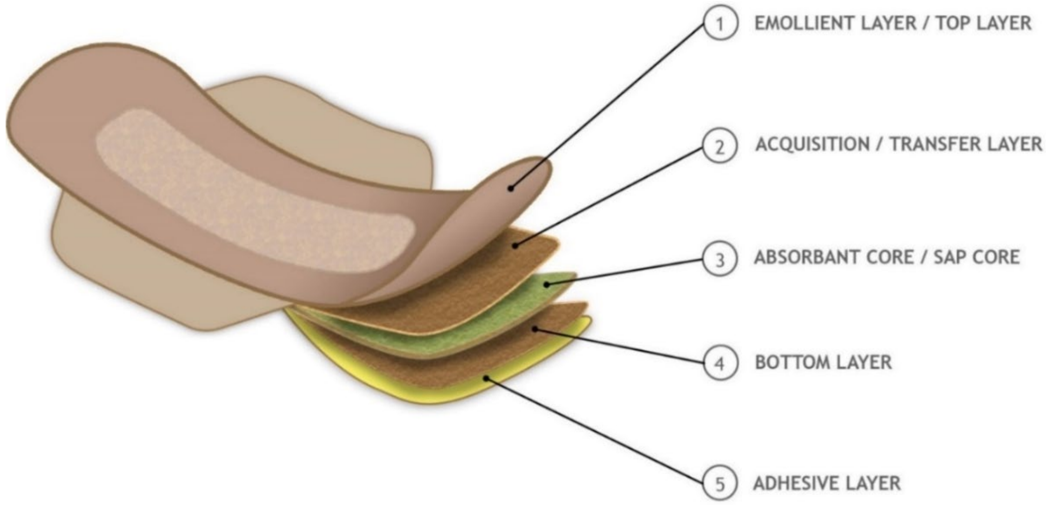


Figure 17: Deconstructed menstrual pad made from *Eichhornia*

Table 3: Recommendations for the most duplicable *Eichhornia* pad.

1	Top layer	Raw cotton, fiberized *Eichhornia*
2	Acquisition Layer	Raw cotton pulp
3	Absorbent core / SAP core	*Eichhornia* -based hydrogels using sodium alginate and a $CaCl^2$ solution
4	Back layer	Raw cotton, fiberized *Eichhornia*
	Impermeable layer	Corn starch, biodegradable film from elephant ear
5	Adhesive layer	Malleable honey strips, soy protein isolate and rosin ester resin combination

5.7 Implications

As one of the world's most notorious invasive aquatic plants, it is also one of the most productive (Jafari 2010; Malik 2007). Harnessing the abilities of *Eichhornia* to duplicate quickly, absorb large quantities of water, and remove heavy metal from waterbodies when fabricating menstrual pads support several Sustainable Development Goals (SDGs). The fabrication of menstrual pads using *Eichhornia* has been done in several countries including Bangladesh (Hossain 2019), India (Rodriguez and Gralki 2019), and Kenya (Global Innovation Exchange 2019). As many people who menstruate face discrimination in the form of shame, educational and workplace exclusion, and limited social mobility while menstruating, having a natural, low-cost, and biodegradable alternative to feminine hygiene products (FHPs) is ideal. As discussed previously, single-use and non-biodegradable FHPs pose their own environmental issues since they are added to landfill waste in the best case or produce other problems if disposed of unproperly.

Sustainable development goals addressed by *Eichhornia* menstrual pads

Through the removal of invasive aquatic plant species, Sustainable Development Goal (SDG) 14, Life Below Water, is supported. According to the United Nations, the number of areas with oxygen levels that are too low to support life, or dead zones, increased from 400 to 700 from 2008 to 2019. Removal of invasive, oxygen depleting plants, such as *Eichhornia*, will reduce the number of dead zones in marine environments. *Eichhornia* blocks waterways, competes with native species for sunlight, and homogenizes flora by lowering the amount of available oxygen, nitrogen, and the water level due to its high evapotranspiration rate (Timmer and Weldon 1967; Van Der Weert and Kamerling 1974). Removal of *Eichhornia* aids in environmental protection and conservation. In ecologically fragile areas with threatened native species, the removal of harmful invasives is key in maintaining the biodiversity and health of aquatic ecosystems. As invasive species compete with native species for resources, invasive species adapt to their environment and develop characteristics that enable them to persist and duplicate more aggressively than their native counterparts. The productivity and adaptability of invasives species are two attributes that make them a major threat to native species.

A feminine hygiene product (FHP) without toxic ingredients supports SDG 3: Good Health and Well-being. Many commercial feminine products are made with harmful additives to increase durability, flexibility, or absorbency. Having a product that is transparent with consumers of the entire process of fabrication is better than a potentially harmful product, full of toxins, whose ingredients do not legally need to be disclosed to the public. Also, many people who menstruate have limited resources during menstruation, so it is common for them to use old rags as pad. In India, around 70% of women cannot afford sanitary pads (Jacob, Khanna, and Yadav 2014), or to purchase new cloth (Garg, Sharma, and Sahay 2001), so slum residents and women in rural areas use rags from old clothes as these materials are immediately available and can be reused. After use, women will wash the rags using water that may be unfit for consumption or usage. Using unpotable water to clean rags and cloth used to absorb menstrual blood could lead to infections within the urinary and reproductive tract systems. Naturally sourced menstrual products without harmful additives promotes women's health and well-being.

Creating affordable menstrual products supports SDGs 5 and 10: Gender Equality and Reduced Inequalities. Inexpensive FHPs supports gender equality because those who do not have the monetary resources to purchase regular FHPs will have an alternative that they can afford. In being able to afford menstrual products, female absenteeism from work and school will decrease because they will be able to remain dignified as they menstruate because discharge and the sanitary product will be hidden. Many females refrain from attending work or school due to the fear of facing ridicule or being ostracized by society when they are menstruating. In feeling more comfortable tending to their societal duties while they are menstruating, gaps between females and their male peers will decrease. For example, it is more common for young girls to miss school and fall behind than boys strictly due to them missing school while they are menstruating (Alam, Luby, Halder et al. 2017; Chandra-Mouli and Patel 2017; Crawford, Menger and Kaufman 2014; Miiro, Rutakumwa, Nakiyingi-Miiro et al. 2018). In many developing countries, adolescent girls miss up to a fifth of the school year or fully drop out which then increases their likelihood of childhood marriage (Cousins 2020) and high birth rates. Being able to manage menstruation discreetly enables females to attend their regular duties without the fear of repudiation from their community.

Although an environmental nuisance in many parts of the globe, the unique abilities of the *Eichhornia* to absorb and clean water quickly and effectively, combined with its high growth rate can instead be seen as a global solution to many issues. One such issue is SDG 6: Clean Water and Sanitation. Within this area lies the Water, Sanitation, and Hygiene (WASH) sector which addresses the lack of affordable, clean, dignifying, and biodegradable menstrual products. An underdiscussed social issue affecting many women and girls is the impact of period poverty. Menstrual health and the lack of affordable FHPs can be addressed in the adoption and modification of ways that *Eichhornia* is used as a sanitary resource. The best plant to use has not been identified, however there are several plant-based pads that have passed the production phase and are now available to be purchased. See Table 4 for a list of plant-based menstrual pads, materials used in their production, and the stage of development.

Table 4: Plant-based menstrual products

Pad Name/ Location	**Plant Used**	**Plant component**	**Stage of Development**	**Website**
LilyPad/ Uganda	*Eichhornia*	Fiber	Locally available	thedeweproject.wordpress.com/the-lily-pads/
JaniPad/ Kenya	*Eichhornia*	Fibers	Locally available	www.trendhunter.com/trends/jani-sanitary-pads
Saathi Pad/ India	Bamboo, Banana Stem	Fibers	Commercially available	saathipads.com
Safe Pad/ India	Banana Stem	Fibers	Commercially available	bioplasticsnews.com/2019/09/01/reusable-biodegradable-sanitary-napkin-banana-fibre/
SHE 'go!' Pad/ Rwanda	Banana Stem	Fibers	Locally available	sheinnovates.com
BanaPads/ Uganda	Banana Stem	Fibers	Locally available	banapads.org

MAKAPad / Uganda	Papyrus	Fibers	Locally available	cedat.mak.ac.ug/research/maka-pads/
PadBack/ South Korea	Papyrus, *Eichhornia*	Fibers	Unknown	cansuakarsu.com/padback

6. CONCLUSION

Although originating from the Amazonian basin, *Eichhornia* has spread to nearly every corner of the globe. The prolific spread of aquatic weeds, specifically *Eichhornia*, is an example of our inability to manage resources properly (Holm, Weldon, and Blackburn 1969), ponder outcomes prior to acting, and of our ignorance of potential risks until they have become actualized. Once the harmful nature of invasive species and the threat they pose to biodiversity became apparent, some argued that the way to manage global biological invasions is through control interventions, such as mechanical, manual, and chemical control, or through isolation of the invasive species (Holm, Weldon, and Blackburn 1969; Kleinschroth, Winton, Calamita et al. 2021). These methods of control are successful to an extent, however the energy and money put into mitigating the damage done by invasives is left without repayment or increase in revenue. Tourism, recreation, and farming will exhibit temporary improvements until efforts to remove the plant commence again.

Once utilization becomes a control method of invasive species, we will find we have an endless supply of natural material to use in a variety of applications and to address a variety of social issues. The innate human desire to create could be paired with the innate desire of invasive species to spread, survive, and outcompete native species. Using *Eichhornia* to fabricate a compostable menstrual pad is just one example of how we can upcycle invasive species into something that benefits people, the planet, and could generate profit.

Until recently, attention on mitigating period poverty has been inadequate. The division between the genders in regard to social mobility, within the workplace, in academia, and even in the household is bolstered by period poverty that some people who menstruate must navigate, knowingly or unknowingly, in all regions of the globe. This phenomenon is not solely a matter of social inequality. As argued here, period poverty and menstrual inequity have adverse health and environmental effects. Areas without proper sanitary facilities are going to be more harmful to the citizens that live there and to the environment in which they habituate compared to areas with sufficient sanitation. Creating menstrual pads from natural resources that are available all over the world addresses period poverty and furthers the progress of developing proper sanitation in regions where the present level of sanitation has negative health and environmental effects.

Discovering ways we can use invasive species to our advantage is a practicable and achievable goal. For many thousands of years humans have modified the environment to better suit their needs. As of recent decades, this desire to retrofit the environment for humans has been paired with an understanding that our present actions could have future consequences. The current infestation of invasive plants is a result of humanity's desire to modify our environment without fully understanding the nature of the invasive species and neglecting the potential negative impacts their presence could have in the future.

However, the mistakes of past generations could be made up for now. We can use invasive species to make products that have positive economic, environmental, and social impact. Creative reuse is the best way to manage unwanted material. Human ingenuity is limitless. We've proven as a species that we are capable of altering entire global systems, that we can connect people within even the most remote locations to each other, and we can always seek to improve. Humans are the only species known to be capable of reversing the effects of global warming and promoting biodiversity. Upcycling invasive species presents us the opportunity to exercise our ingenious nature to improve and create while also promoting the health of the planet and each other.

APPENDIX SECTION

APPENDIX A: UPCYCLING APPLICATIONS OF *EICHHORNIA*

Many applications of the *Eichhornia* utilize the plant's water retention and filtration ability. Many studies have indicated the potential of *Eichhornia* in sanitary applications (Rodriguez and Gralki 2019), agriculture (Jafari, 2010; Rakotoarisoa, Richter, Schmidt et al. 2020), wastewater treatment and water quality (Gong, Zhou, Ma et al. 2018; Jafari, 2010; Rommens, Maes, Dekeza et al. 2003), as biofuel (Gunnarsson and Petersen 2007; Malik, 2007; Nigam 2002), animal feed, and in the sorption of dyes (Guna, Ilangovan, Anantha Prasad et al. 2017). Around the globe, specifically in developing and emerging developing countries, there is a large body of research indicating the potential of *Eichhornia* in an array of useful applications. Several applications of *Eichhornia* will be examined.

Some practices of *Eichhornia* management include controlled harvesting of the plant (Gunnarsson and Petersen 2007) and using it as a composting component. The quality of compost from *Eichhornia* is within industry standard ranges (Montoya, Waliczek, and Abbott 2013) and has shown to increase crop yields (Malik 2007; Rakotoarisoa, Richter, Schmidt et al. 2020). When *Eichhornia* is being used to produce commodifiable items or tools, small-scale aquatic farms can be constructed to isolate areas where it will grow. It can be made into feed for livestock, usually pigs, by mechanically grinding dried stems into pellets or hay. There is high calcium and Vitamin A content within the leaves and *Eichhornia* exhibits good digestibility.

Eichhornia has proven to a successful component for phytoremediation (Jianbo, Zhihui and Zhaozheng 2008; Malik 2007; Rezania, Ponraj, Talaiekhozani et al. 2015;

Ting, Tan, Salleh et al. 2018). The roots system of the plant absorb water along with heavy metals such as cadmium, lead, mercury, zinc, iron, silver, arsenic, chromium, and copper (Lissy and Madhu 2011), pathogens, and sewage (Rommens, Maes, Dekeza et al. 2003). Green remediation technologies such as phytoremediation often employ unexpected plant species. The natural inclination of the *Eichhornia* to absorb water has been taken advantage of and utilized in positive ways. *Eichhornia* causes high rates of evapotranspiration and other environmental issues, but also can assist in sustainable management and treatment of wastewater (Rezania, Ponraj, Talaiekhozani et al. 2015). The Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), nitrate and phosphate content, fecal coliform content, color, and odor of effluent treatment using *Eichhornia* culture have been measured. The study indicated drastic reductions in BOD and COD and a reduction in fecal coliforms by 80%. The nitrogen and phosphorus content rose by over 75% and 60% respectively while the water went from a yellowish color to clear, and the original odor disappeared (Alade and Ojoawo 2009). Phytoremediation is a popular tactic used for wastewater treatment in developing countries. Utilizing plants to improve water quality is less expensive than adding chemicals to manage effluent.

Utilizing plant material with high cellulose content to produce biofuel is a sustainable alternative to pollution producing nonrenewable resources. The high cellulose content of *Eichhornia* makes it a useful component in biomass to produce cellulosic ethanol as well as in the production of biogas (Rezania, Ponraj, Talaiekhozani et al. 2015). Lignocellulose is a commonly used raw material in the production of ethanol because of its wide availability and low cost. Using the lignocellulose within *Eichhornia* produces fuel ethanol with lower toxicity and emissions than petroleum. Production of fuel ethanol using *Eichhornia* does not release as much carbon dioxide into the atmosphere as petroleum production or producing ethanol from other sources (Nigam 2002). Its hemicellulose content is high compared to other plants used in biomass production. It also provides nitrogen during the bioconversion processes due to its high crude protein content (Nigam 2002). Much of the literature on *Eichhornia* as an ingredient in biofuel has been undergone in India or in parts of Africa. As the Earth's supply of non-renewables dwindles, reliance on external sources will increase. *Eichhornia* is a quickly replenishing resource used in fuel ethanol production and should be used far more prolifically.

The cellulose fibers exhibit tremendous absorptive capabilities in sanitary applications of textiles. The stem produces very long fibers which have been used within the textile industry (Chonsakorn, Srivorradatpaisan and Mongkholrattanasit 2019), to create rugs and furniture, and in the production of sanitary pads (Hossain 2019; Rodriguez and Gralki 2019; Team 60 2014). These fibers can be harvested from the petiole of the plant and used in a variety of applications. Many studies indicate the favorability of using the cellulose fibers in the fabrication of sanitary pads due to it being lightweight, highly absorptive, and biodegradable. Isolating the cellulose fibers requires pretreatment. This process consists of the removal of hemicelluloses, pectin, and lignin using acidified sodium hydroxide and sodium chlorite solutions (Thiripura Sundari and Ramesh 2012).

Eichhornia has been used in the biomedical field to make cellulose-based hydrogels. Biopolymer-based hydrogels include protein hydrogels, such as gelatin and collagen, and polysaccharide hydrogels, such as chitosan and cellulose. As environmental conditions worsen, the favorability of biopolymer-based hydrogels will continue to increase due to their biodegradability and abundance. Cellulose-based hydrogels have been used to replace tissues, organs, and to aid in normal body function (Kabir, Sikdar, Haque et al. 2018). *Eichhornia* is a favorable resource for cellulose-based hydrogel creation due to its high cellulose content, abundance, and environmental incentive of removal.

APPENDIX B: WATER, SANITATION AND HYGIENE

Interpreting SDG 6, ensuring the availability and sustainable management of clean water and sanitation for all, as a solely subjective goal is underestimating the extent of factors that influence an individual's or group of peoples' accesses to these basic rights. WASH, and all that fall under this umbrella term, is a confluence of issues stricken by poverty, culture, social perceptions, a lack of education, and gender inequality. Areas that are impoverished are more likely to have inadequate sanitation and water access. Places where public sanitary facilities are unkept and toilets are misperceived are more likely to have higher rates of open defecation. Regions that are heavily influenced by social stigmas that limit the social mobility of people, specifically women, are more likely to have sanitation issues. Areas where women and men are not educated on the process of menstruation are more likely to have inadequate sanitation and water access. Several countries have cultural norms that exacerbate the diminution of women and favoritism of males. A skewed vision of a woman's "purity" has led to gender inequality in employment (Jayachandran 2015), school, and society. The structures set in place to protect this vision of purity limits women's mobility. Questions then arise on whether the limitation in mobility is to protect women from violence, be chivalrous, uphold religious beliefs, or if it's a way to maintain the weakness of female autonomy (Jayachandran 2015).

Addressing period poverty, menstrual health, and sanitation are key factors within the sector of WASH. A solution that meets the needs of those directly experiencing the effects of these problems needs to be adoptable, easy to access, discrete, and eco-friendly.

Examining period poverty, menstrual hygiene management, and sanitation insecurity are important in fully addressing WASH and the connection between menstruation, sanitation, and human rights.

The connection between sanitation and its connection to gender, period poverty, and menstrual hygiene management will be examined in India, a developing country that is arguably the most discussed location of sanitation issues, and the United States, a developed country that still has progress to be made regarding menstrual health awareness and in addressing period poverty.

Sanitation

Every year, over 2.2 million people, mostly children, die from diseases related to poor hygiene, sanitation, and water (Brewster, Herrman, Bleisch et al. 2007). Access to safe water and sanitary facilities is recognized as a human right by the United Nations. The right to drinking water was officially recognized as a human right in 2010 by the UN General Assembly and the right to sanitation was recognized in 2015. According to the UN, the right to water entails every individual's access to dependable, safe, and affordable water. The right to sanitation entitles everyone to have a physically accessible, safe, hygienic, and socially and culturally acceptable, private sanitary space. The way that countries and local governments meet these requirements is bound by the interpretations and financial situation of each location. Inditing sanitation and access to drinking water as human rights invokes policy reframing. International organizations stress the necessity of a rights-based approach to health (Meier, Kayser, Amjad et al. 2013), leading to global standards and facilitating global accountability under international law (Alston and

Robinson 2005). The human right to water and sanitation evolved from the International Bill of Human Rights, which is a compilation of three documents: the Universal Declaration of Human Rights (UDHR), the International Covenant on Civil and Political Rights (ICCPR), and the International Covenant on Economic, Social and Cultural Rights (ICESCR) (Alston and Robinson 2005). The UDHR set the forefront for a "standard of achievement for all peoples and all nations" (United Nations 1948). This was a non-binding declaration that led to the development of legal documentation, the ICCPR and ICESCR. The accumulation of these three documents is the basis for the international human rights system (Alston and Robinson 2005). International discourse within the rights to water and sanitation arena stresses equitable sharing of resources.

As the parameters for an international medium on water and sanitation have been elucidated, separate parameters have been created that are used to describe the state of sanitation in individual countries. One such parameter is the sanitation insecurity measure. This measure accounts for the many variables that have an effect on the quality of sanitation an individual has access to.

Assessment of sanitation insecurity

Sanitation insecurity has been used to describe the sanitary state of India. This term was developed by Caruso, Clasen, Yount et al. (2017) to include the influence of gender in the evaluation of a nation's sanitary state and refine the definition of sanitation. According to Caruso, Clasen, Yount et al. (2017), sanitation insecurity is:

"*Insufficient and uncertain access to a socio-cultural and social environment that respect and respond to the sanitation needs of individuals, and to adequate physical spaces and resources for independently, comfortably, safely, hygienically, and privately urinating, defecating, and managing menses with dignity at any time of day or year as needs arise in a manner that prevents fecal contamination of the environment and promotes health*."

This definition is expanding this area of study as it covers the multiple dimensions that influence women's experiences with sanitation. The sanitation needs of a country needs to be communicated by multiple groups of people. All genders, economic statuses, and all ages need to be represented when making decisions regarding sanitation. In most countries categorized as "developing", people who menstruate are often not included in decision making groups. For example in rural Odisha, India, women are often marginalized and have no decision-making power (Caruso, Clasen, Yount et al. 2017; Vogel, Hwang, and Hwang 2022). Underrepresented and placed in a diminutive position, women and marginalized groups are unable to speak on their behalf and their experience with sanitation and policies set in place continue to reproduce sexual divisions (Swaminathan 1987; Vogel, Hwang, and Hwang 2022). Negative attitudes and perceptions of both men and women on menstruation and femininity limits the social mobility of women.

Improved and unimproved sanitation

The terms "improved" or "unimproved" are used to describe the state of sanitation in an area. An environment with subpar, called unimproved, sanitation lacks a toilet, or has a toilet that does not separate human excrete from human contact (Caruso, Clasen, Hadley et al. 2017; Caruso, Clasen, Yount et al. 2017), is not piped to a sewer system, is a bucket, or a hanging toilet. A shared facility, no facilities, or use of an open field is also considered unimproved sanitation (Vogel, Hwang, and Hwang 2022). Improved sanitation is the presence of a toilet connected to a working, piped sewer system or having a composting toilet (CIA 2021; Vogel, Hwang and Hwang 2022). Around 4.2 billion people, 55% of the world population, lack access to improved and safely managed sanitation. Over 494 million people practiced open defecation globally in 2020 (UN-Water 2021). According to The World Factbook, 28% of the total Indian population does not have access to improved sanitation, totaling 6.3% of the urban population, and 38.9% of the rural population. In the US, 100% of the country has access to improved sanitation.

The improved versus unimproved categorization of sanitation does not include the consideration that owning a toilet does not equate that the toilet is being used (Vogel, Hwang, and Hwang 2022). Women who practice open defecation are placed in a vulnerable position and are at risk of sexual assault and being attacked (Saleem, Burdett, and Heaslip 2019).

Sanitation insecurity furthers the limited terms of improved versus unimproved sanitation when describing the state of sanitation by accounting for the multiple constraints that limit individuals, specifically females, from having access to proper sanitation facilities and practicing safe menstrual hygiene management (MHM).

Inadequate Water, Sanitation, and Hygiene (WASH) systems are not symptoms of poverty. They are barriers to the reduction of poverty and development. One way to address several WASH-related issues is through an individualized approach: providing a naturally sourced, affordable, chemical free, biodegradable alternative to plastic-based feminine hygiene products (FHPs). Within developing countries, a major inhibitor to females attending work or school as often as their peers is a lack of menstrual products that promote dignity and are financially obtainable. Several studies have found that providing free sanitary products to young girls decreased rates of absenteeism in school (Anderson 2016; Montgomery, Hennegan, Dolan et al. 2016). In all countries, females using menstrual products from major companies are put at risk from the toxins added to increase product performance or appeal. After use, these products are disposed of, properly or unproperly, and ultimately end up within landfills, bodies of water, or in sewer systems. The chemicals then infiltrate drinking water, groundwater, and soil. Known persistent organic pollutants, dioxins and furans, that are used in feminine products are a threat in every stage of the product's life cycle.

APPENDIX C: UPCYCLING INVASIVE SPECIES

As natural resources become more limited and their usage causes climate change, other resources must be used instead that do not induce the same environmental effects as petroleum, natural gas, and coal. However, a tactic to speed the process of depending less on non-renewables is through finding alternative sources for energy and goods. As long as present needs and demands are met, the source of energy does not matter. A problem arises in the source of energy supply when said supply is not equal to what people have become accustomed to. There are many other resources we could be using as alternatives to non-renewables. The usage of invasive species to produce biofuel, material goods, medicine, aid in agricultural improvements, and improve water quality have been studied extensively. However, global attention to invasive plants as an environmentally friendly, and cheaper, alternative to non-renewables is far from where it needs to be. To slow and eventually reverse the effects of global warming, we must learn to utilize other sources of energy and production.

We need diversity to maintain global balance and sustainability. Reliance on any single or a group of a few resources, specifically referring to fossil fuels, is cause for global problems as those resources reach their end.

Although viewed as the origin of many issues, employing other schools of thought enables us to see the usefulness of invasive plants. The worst environmental problems were induced by human activity. The solutions to these problems will also require human activity. Studying the interactions of humans with the physical environment elucidates how influential human behavior and perception is over the health of the world. The following section reviews several invasive aquatic species found within the San Marcos River including their origins, effect on river ecology, control methods, and upcycling applications of each aquatic plant.

Hydrilla (*Hydrilla verticillate)*

Figure 18: *Hydrilla verticillata* in the San Marcos River.

First discovered in the US in the 1960s, hydrilla, *Hydrilla verticillate* (Figure 21), is coined "the perfect aquatic weed" due to its high adaptability to many aquatic environments. Hydrilla often root themselves but can survive free-floating. Polymorphous hydrilla are sometimes unrecognizable as the physical appearance of the plant can vary depending on the aquatic conditions (Langeland 1996). According to the USDA, hydrilla is the most abundant and dangerous aquatic weed. In 1976, the first male hydrilla was identified in the US. Until then, female hydrillas, dioecious types, were the only type found in waterways. The dioecious types originated from India, with records indicating the island of Sri Lanka and southern India as exact origins. In the early 1950s, the plant was brought into the US to be used in aquariums; from there, the plant spread to lakes, pods, rivers, canals when the plant was discarded or planted (Jacono, Richerson, Howard et al. 2020). Hydrilla travels to different freshwater bodies as stem pieces stick to boats and then root in the new area. The plant is commonly found around boat ramps. Today, it has infested waterways in every continent besides Antarctica (Balciunas, Grodowitz, Cofrancesco et al. 2002; Cook and Lüönd 1982), and 28 states in the US.

The Edwards Aquifer Habitat Conservation Plan focuses on improving river quality through projects such as invasive species removal along the banks and within the river (EAHCP, n.d.). The Habitat Field Crew removes hydrilla along a 1.5-mile stretch of the SMR and within Spring Lake. This species is the primary invasive in the SMR as it can persist even after the plant is removed if the root structure stays intact or fragments remain in the water.

Hydrilla is a perennial, rooted, long stemmed plant with tissue comprised of about 30% cellulose, 20% hemicellulose, and 10% lignin (Table 1). The root system is simple, long, white or brown, and grows out of hydrosoil or within nodes. Should a hydrilla become detached from the mat or its root system, it will travel and infest a different area. Stolons beneath the soil are asexual and resistant to herbicides. The buried stolons lead to quick regrowth of areas that have been cleared (Balciunas, Grodowitz, Cofrancesco et al. 2002). Visible stems are slim and grow in length quickly. Branches form along the base of the stem. The leaves are small and verticillate, growing in nodes along the stem in whorls with visible teeth along the edges. During unfavorable conditions, the plant will travel as seeds or in hibernacula in the form of a protective brown bud (Cook and Lüönd 1982). The seeds, each 2-3 mm long, form in a linear sequence of up to 5. Hibernacula forms in two ways: as a brown bulb at the end of a stolon (tubers) or as a green cone at the axils of branches (turions) (Balciunas, Grodowitz, Cofrancesco et al. 2002). Hydrilla can be dioecious, producing only female flowers, or monoecious, producing both male and female flowers.

Female flowers require air pollination. As the flower stalk, or hypanthium, breaches the surface, the female flower becomes bell-shaped as it grows beyond the surface with an air bubble enclosing the stigmas. Male flowers do not have a hypanthium, so the bulb detaches from the stalk and floats to the surface to release pollen. Areas with male hydrilla become greenish white from the pollen and discarded bulbs floating in the water. Rapid growth of the plant is due to its ability to form adventitious roots out of small stem fragments (Balciunas, Grodowitz, Cofrancesco et al. 2002). Hydrilla grow best in calcareous water but can grow in both acidic and alkaline conditions. Edwards Aquifer is a karst aquifer, formed from carbonate limestone, therefore the conditions of the SMR are favorable for hydrilla infestation. The plant is genetically variable and can adapt to the conditions of its environment (Cook and Lüönd 1982). The trait of physiological differentiation allows the plant to wreak havoc in many parts of the globe.

Factors controlling hydrilla growth are water depth, clarity, and velocity of stream flow. In areas such as Spring Lake where water clarity is high, deep-water extraction of the plant is required. Hydrilla has been observed to grow at depths around 12 meters in clear water (Haller 2009). Hydrilla obstructs stream flow, reduces dissolved oxygen

(Bradshaw, Allen and Netherland 2015), changes water chemistry (Smart and Barko 1988) and decreases fish populations. Post hydrilla removal, juvenile fish populations have shown to increase (Johnson, Dotson, Pouder et al. 2014). The plant causes habitat alterations by limiting the amount of sunlight native plants receive, decreasing consumer populations (Posey, Wigand, and Stevenson 1993), slowing the flow rate of rivers and streams, and reducing biodiversity by competing with native plants. Hydrilla has been observed to increase in invasiveness and density when water temperatures increase (Calvo, Mormul, Figueiredo et al. 2019) and when the carbon content is at a higher level (Smart and Barko 1988).

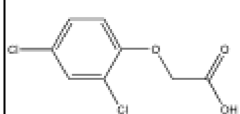
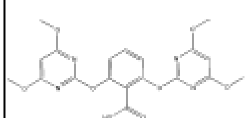
Manual, biological, mechanical, and chemical control are used to mitigate hydrilla populations. Insects, such as moths, grass eating carp, and pathogens have shown to mitigate population sizes. Biological combined with chemical control has proven to be the most successful in sustaining hydrilla removal (Haller 2009; (Manuel, Kirk, Barwick et al. 2013). Along the SMR, manual removal has been incredibly successful in eliminating hydrillas. The only grass eating carp allowed in Texas are triploid grass eating carp; a permit must be obtained by the Texas Parks and Wildlife Department before purchasing (AgriLife 2021). Grass eating carp have not been used as a control method within the SMR.

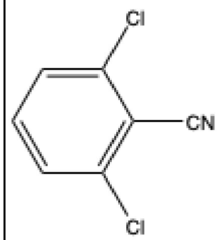
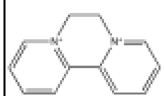
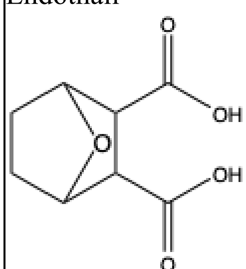
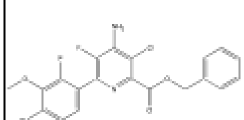
A study funded by The Army Corps of Engineers Waterways Experiment Station found that of the 200 species of insects collected along sites where hydrilla were growing, only 15 fed on the invasive plant (Balciunas, Grodowitz, Cofrancesco et al. 2002). Due to the plant’s physiological variability, a consistent biological control agent may not be present. Effective control agents will vary based on location and genetic variation of hydrilla. Parasitic larvae of moths and flies have shown to decrease hydrilla growth as they feed on the leaves of the plant (Bownes 2010; Coon, Harms, Cuda et al. 2014). Grass eating carp are typically utilized in lakes or ponds and are effective in reducing hydrilla populations (Haller 2009; Schad and Dick 2018). A drawback with triploid grass eating carp, a generalist species, is that it eats substantial amounts of plants and can alter the aquatic community (Dibble and Kovalenko 2009). The carp can feed on untargeted plants and eliminate entire species (Schad and Dick 2018; Haller 2009; Pipalova 2006; Bonar, Sehgal, Pauley et al. 1990). No present studies have identified insects or pathogens in the SMR that reduce hydrilla populations.

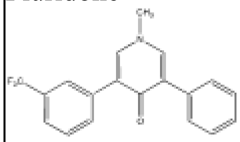
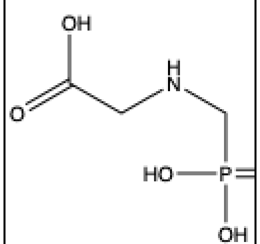
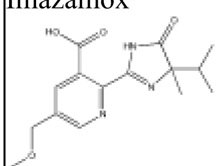
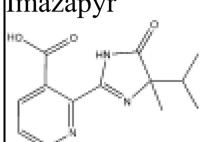
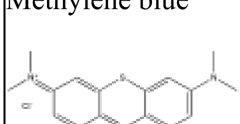
Mechanical control of hydrilla can be costly and inefficient. Some mechanical equipment can only cut to a depth of 1.5 meters so uncut hydrilla will grow back quickly at a rate of 2.5 cm per day (Haller 2009). Plants that are submerged will regrow from remaining fragments, so the removal of these fragments is needed to ensure hydrilla does not repopulate the same area (AgriLife 2021).

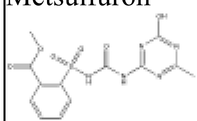
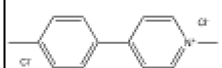
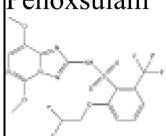
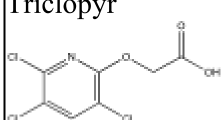
Research indicates many herbicides mitigate hydrilla growth without harming fish populations (Gangstad 1978). According to Texas A&M AgriLife Extension, active ingredients that are successful in managing hydrilla are penoxsulam, bispyribac, imazamox, Cu, fluridone, endothall, and diquat (Table 6). These chemicals have received a rating from the US Army Corps of Engineers aquatic herbicide trials. Cu, diquat, and endothall are typically used in treatment along the shore or in spots and result in rapid decay of the plant. Penoxsulum, fluridone, and imazamox control enzyme activity and are used in large-enclosed areas where prolonged exposure is possible (Haller 2009). Testing fluridone and endothall indicated the chemicals are not acutely toxic to certain species of mollusks (Archambault, Bergeron, Cope et al. 2015). Dyes such as methylene blue have proven to decrease plant growth because the dyes limit the amount of sunlight reaching the plant (Barltrop, Martin, and Martin 1982). Unintended outcomes such as oxygen depletion may result from herbicidal use. The decomposition of the dead plant material causes lower oxygen levels which can harm fish populations in smaller bodies of water.

Table 5: Chemicals used for chemical control of invasive plants

Chemicals	**Characteristics and Effects**[1]	**Target Species**
2,4-D 	• Appearance: tan or white crystalline solid • $C_8H_6Cl_2O_3$ (CAS#: 94-75-7), Molecular weight: 221.03, Melting point: 280 ºC, Decomposition point: 160 C • Harmful effects o Humans: eye damage, eye irritation, specific organ toxicity, respiratory tract irritation, gastroenteric distress, diarrhea, dysphagia, and skin irritation (Exposure route: inhalation, dermal, oral, eye) o Environmental: hazardous air pollutant, hazardous water pollutant, long-term effects to environment	*Eichhornia crassipes*, *Colocasia esculenta*
Bispyribac 	• Appearance: White powder • $C_{19}H_{18}N_4O_8$ (CAS#: 125401-75-4), Molecular weight: 430.37, Melting point: 148-150 ºC, Decomposition point: 223 ºC • Harmful effects o Humans: seizures, respiratory insufficiency, pulmonary edema, respiratory arrest, vomiting, eye irritation, and skin burns (Exposure route: inhalation, dermal) o Environmental: absorbs suspended solids and sediment in aquatic environments, low bioconcentration	*Hydrilla verticillata*, *Eichhornia crassipes*

Dichlobenil  	• Appearance: White crystalline solid • $C_7H_3Cl_2N$ (CAS#: 1194-65-6), Molecular weight: 172.01, Melting point: 145-146 ºC, Decomposition point: stable to heat • Harmful effects o Humans: cancer, eye redness, cough, chloracne, respiratory insufficiency, respiratory arrest, pulmonary edema (Exposure route: inhalation, dermal) o Environmental: soil penetration, groundwater contamination, varying half-life	*Alternanthera philoxeroides*
Diquat 	• Appearance: Yellow crystalline solid $C_{12}H_{12}N_2^{+2}$ (CAS#: 85-00-72764-72-9), Molecular weight: 184.24, • Melting point: < 320 ºC, Decomposition point: 320 ºC • Harmful effects o Humans: eye irritation, skin irritation, vomiting, diarrhea, malaise, kidney damage, liver damage, pulmonary edema, dyspnea, convulsions, death (Exposure route: inhalation, dermal, oral ingestion) o Environmental: could affect unintended plants species	*Hydrilla verticillata, Pistia stratiotes, Colocasia esculenta, Eichhornia crassipes*
Endothall  	• Appearance: white crystalline solid $C_8H_{10}O_5$ (CAS#: 145-73-3), Molecular weight: 186.16, • Melting point: 144 ºC, Decomposition point: 144 C ºC • Harmful effects o Humans: respiratory irritation, eye irritation, skin irritation, eye damage, skin corrosion, organ toxicity, death (Exposure route: dermal, oral ingestion, inhalation) o Environmental: biodegrades in soil, low bioconcentration in aquatic biota, half-life of 1 week in aquatic systems	*Hydrilla verticillata*
Florpyrauxifen-benzyl 	• Appearance: white crystalline solid • $C_{13}H_8Cl_2F_2N_2O_3$ (CAS#: 1390661-72-9), Molecular weight: 349.11, Melting point: 154.5 ºC, Decomposition point: 200-219 ºC • Harmful effects o Humans: skin irritation, respiratory distress, eye irritation (Exposure route: dermal, inhalation) o Environmental: lasting toxicity to aquatic biota	*Eichhornia crassipes*

Fluridone 	• Appearance: white crystalline solid • $C_{19}H_{14}F_3NO$ (CAS#: 59756-60-4), Molecular weight: 329.3, Melting point: 154.5 ºC, Decomposition point: 200-219 ºC • Harmful effects o Humans: skin irritation, respiratory distress, eye irritation (Exposure route: dermal, inhalation) o Environmental: lasting toxicity to aquatic biota	*Hydrilla verticillata*
Glyphosate 	• Appearance: white powder/crystals • $C_3H_8NO_5P$ (CAS#: 1071-83-6), Molecular weight: 169.07, Melting point: 230 ºC, Decomposition point: 230 ºC • Harmful effects o Humans: eye damage, eye irritation, skin irritation (Exposure route: eyes, dermal exposure) o Environmental: lasting effects to aquatic environments, mobility in soil, varying half-life, low bioconcentration, groundwater contamination	*Alternanthera philoxeroides, Pistia stratiotes, Colocasia esculenta, Eichhornia crassipes*
Imazamox 	• Appearance: off-white powder • $C_{13}H_{15}N_3O_3$ (CAS#: 114311-32-9), Molecular weight: 261.28, Melting point: 166 ºC, Decomposition point: decomposes in sunlight • Harmful effects o Humans: not a significant eye/nose/skin irritant (Exposure route: respiration, dermal contact) o Environmental: very toxic to aquatic life, lasting effects to aquatic life	*Hydrilla verticillata, Eichhornia crassipes*
Imazapyr 	• Appearance: clear-pale yellow or dark green liquid, tan to white powder • $C_{15}H_{19}N_3O_4$ (CAS#: 81334-34-1), Molecular weight: 305.33, Melting point: 171 ºC, Decomposition point: N/A • Harmful effects o Humans: eye irritation, eye damage, skin irritation (Exposure route: eyes, dermal) o Environmental: hazardous to aquatic life, lasting effects to aquatic life, high soil mobility	*Eichhornia crassipes*
Methylene blue 	• Appearance: dark green crystals/ powder • $C_{16}H_{18}ClN_3S$ (CAS#: 61-73-4), Molecular weight: 319.9, Melting point: 100-110 ºC, Decomposition point: 100-110 ºC • Harmful effects o Humans: acute oral toxicity, eye damage, eye irritation, nausea, vomiting, abdominal pain,	*Hydrilla verticillata*

	dizziness, hypertension, headache, excessive sweating (Exposure route: oral, eyes) o Environmental: low bioconcentration, infiltrates groundwater	
Metsulfuron 	• Appearance: off-white granule • $C_{13}H_{13}N_5O_6S$ (CAS#: 79510-48-8), Molecular weight: 367.34, Melting point: N/A, Decomposition point: N/A • Harmful effects o Humans: N/A (Exposure route: N/A) o Environmental: N/A	*Alternanthera philoxeroides*
Paraquat 	• Appearance: yellow or off-white powder • $C_{12}H_{14}N_2^{+2}$ (CAS#: 4685-14-7), Molecular weight: 186.25, Melting point: 300 ºC, Decomposition point: 175-180 ºC • Harmful effects o Humans: skin irritation, respiratory irritation (Exposure route: inhalation, dermal) o Environmental: very toxic to aquatic life, lasting effects to aquatic environment, high soil mobility	*Eichhornia crassipes*
Penoxsulam 	• Appearance: off-white • $C_{16}H_{14}F_5N_5O_5S$ (CAS#: 219714-96-2), Molecular weight: 483.4, Melting point: 223-234 ºC, Decomposition point: decomposes under fire/evaporation conditions • Harmful effects o Humans: skin irritation, respiratory irritation (Exposure route: inhalation, dermal) o Environmental: very toxic to aquatic life, lasting effects to aquatic environment, high soil mobility	*Hydrilla verticillata*, *Eichhornia crassipes*
Triclopyr 	• Appearance: colorless/white crystals • $C_7H_4Cl_3NO_3$ (CAS#: 55335-06-3), Molecular weight: 256.5, Melting point: 148-150 ºC, Decomposition point: 208 ºC • Harmful effects o Humans: skin irritation, allergic reactions, eye damage, eye irritation, target organ toxicity (Exposure route: oral, dermal, eyes, inhalation) o Environmental: very toxic to aquatic life, lasting effects to aquatic environment	*Colocasia esculenta, Eichhornia crassipes*

Triclopyr triethylamine salt 	• Appearance: amber or colorless liquid • $C_{13}H_{19}Cl_3N_2O_3$ (CAS#: 57213-69-1), Molecular weight: 357.7, Melting point: N/A, Decomposition point: N/A • Harmful effects o Humans: eye irritation, eye damage, target organ toxicity (Exposure route: eyes, ingestion, dermal) o Environmental: hazardous to aquatic environment, acute hazard, long-term hazard	*Alternanthera philoxeroides*

Sources: [1] PubChem

Hydrilla can be removed using rakes, cutters, and by hand. Ensuring the entirety of the plant is removed is important because small stem fragments can multiply if rooted. Turions or tubers covered by sediments will quickly reinfest the site if unremoved. Along the SMR, hydrilla is removed by hand in both shallow and deeper waters. The water clarity of the SMR is high because it originates from several springs emerging from the Edwards Aquifer. This allows hydrilla to grow at deeper depths because sunlight is not being prohibited from reaching the invasive plant. To remove hydrilla in deep water, scuba divers dive down to the bottom of the SMR or Spring Lake and manually extract the weed.

Hydrilla is 95% water and 5% dry matter (Haller 2009). The high water-content limits the potential of hydrilla to be upcycled into a useful product such as mulch, feed, or biofuel. Most applications of hydrilla utilize its ability to absorb heavy metals and other metals.

Studies indicate that hydrilla can serve as a heavy metal hyperaccumulator (Shrivastava and Srivastava 2021; (Song, He, Chen et al. 2018) decreases lead at low concentrations (Chathuranga, Dissanayake, Priyantha et al. 2014), removes chromium and cadmium (Rai, Tripathi, Sinha et al. 1995), certain types of dyes (Low, Lee, and Heng 1994; Rajeshkannan, Rajasimman, and Rajamohan 2011), and polycyclic aromatic hydrocarbons such as phenanthrene and pyrene (He and Chi 2019). As hydrilla absorbs some metals, its chlorophyll level decreases (Rai et al. 1995). The ability of the plant to absorb materials, such as Pb, is influenced by the river's pH. The ideal pH for lead biosorption to take place is 4.0 (Chathuranga, Dissanayake, Priyantha et al. 2014) as Pb dissolution occurs best at levels of high acidity. Hydrilla grows best in a weak alkaline environment with a pH of 8.5 (Table 1). Acidity levels of pH 5.5-6.5 adversely affect the plant's metabolism (Song et al. 2018). The pH of the SMR ranges within a neutral state of 6.5-8 which allows for hydrilla to grow prolifically.

The biomass of hydrilla is 95% water so its biofuel potential is low (Gettys and Enloe 2016). Hydrilla mats can weigh up to 15 tons per acre but only produce 1.5 tons of dry matter. This low production of biomass makes the utility of the plant low. Studies have indicated pyrolysis has been successful in converting hydrilla into charcoal and bio-oil (Hu, Chen, Li et al. 2015; Promdee, Phihusut, Monthienvichienchai et al. 2018). However, conducting pyrolysis on hydrilla with a higher nitrogen or carbon content can emit nitrous oxide and sulfur dioxide emissions or corrode the reactor (Damartzis, Vamvuka, Sfakiotakis et al. 2011). The chemical composition of hydrilla varies depending on its environment so measuring the composition prior to biofuel generation is necessary.

The rich nitrogen content of hydrilla makes it a useful product to include in compositing. Its low biomass causes it to not generate much of a product after the composting process, however it does pose benefits when combined with carbon-rich agents such as dry leaves, wood chips, or grass (Jain and Kalamdhah 2019). The hydrilla extracted from the SMR is sent to Bobcat Blend, a composting site owned and operated by Texas State students and faculty.

Alligator weed (*Alternanthera philoxeroides*)

Figure 19: *Alternanthera philoxeroides* in the San Marcos River.

Alligator weed, *Alternanthera philoxeroides* (Figure 22), an aquatic or riparian pest from South America, was first discovered in the US in Alabama in 1897. The following year it was spotted in New Orleans (Buckingham 1996). Competition with *Eichhornia* slowed the spread of alligator weed until the 1940s when herbicides started to be used on the invasive plant. Alligator weed exhibited a higher resistance than *Eichhornia* to common herbicides. Alligator weed replaced *Eichhornia* in areas where *Eichhornia* once had grown prolifically. This aggressive invader is prevalent on land and in water all over the globe and is thought to be the world's first aquatic weed (Tanveer, Ali, Manalil et al. 2018). Today, alligator weed infests aquatic and riparian ecosystems in California, Texas, along the Southeast, North Carolina, Tennessee, Kentucky, Maryland, Arkansas, Oklahoma, and Virginia (USGS 2021). In the SMR alligator weed impedes the natural flow of the river, provides a habitat for mosquitoes, and competes with native flora. According to the Guadalupe Blanco River Authority (2013), alligator weed persists in large colonies downstream and upstream of Martindale within the SMR Watershed.

Alligator weed grows in colonies with an ability to cover large segments of the river's surface and along the banks. A small white flower is the common identifier of this invasive plant. The flower is a bundle of slender filaments that are immobile within bractlets. The stem is hollow and comprised of many nodes where roots, other stems, and leaves take form. In riparian systems, the stems lie along the ground and curve slightly upward. In aquatic form, the hollow stem allows the plant to float at or just below the surface (AgriLife 2021). Stems have been observed to grow up to 1.2 meters t high from the water surface. As alligator weed expands by growing stems from nodes, surface coverage is rapid. The smooth leaves are elliptic and grow opposite from each other. The adventitious root system possesses diarch, triarch, and tetrarch systems within the vascular bundles (Yang, Yang, Zhang et al. 2019). The plant's ability to sprout stems and roots from a prevalence of nodes causes it to spread quickly and cover large sections of water and land.

Roots grow out of nodes along the slender stem to absorb nutrients. More roots will form depending on the energy intake of the plant. As more photosynthetic leaves form and flowers bloom, more roots will grow out of the nodes. Alligator weed will colonize when an apical or axillary stem breaks off and roots form (Julien, Skarratt, and Maywald 1995). The seeds produced by the weed are unviable, so asexual reproduction is the main method of spread. Most clonal plants lose their ability to reproduce sexually as these parts degrade from the lack of use. The weed grows most prolifically in temperature climates. The weed can tolerate temperatures ranging from 10-20 oC but optimal growth occurs at around 26.6 ºC (CABI 2021). Along the SMR, alligator weed growth occurs during the warmer months from March-September, then begins to die off in the colder months. As a perennial plant, regrowth occurs once conditions become favorable if a root system stays intact, or a stem remains viable and contains a node. Because the weed can grow on land and in water, its spread is nearly imminent, and control of the pest is difficult. Riparian alligator weed can withstand long periods of drought, surviving as long as 6 consecutive months with <40mm of rainfall (CABI 2019). The occasionally erratic weather conditions along the SMR are unphased by the tolerant weed.

Alligator weed impedes the flow of water, decreases biodiversity, limits recreation activities such as fishing, boating, and tubing, and can cause flooding as water levels rise. Because the plant forms colonies within waterways, the movement of water slows down and can rise quickly during a flood event. The many endangered aquatic species that the SMR harbors are threatened by this pest. The hollow stems of the alligator weed cause it to form dense mats along the surface of water, preventing underlying flora from obtaining sunlight. The main competition for alligator weed is the *Eichhornia*, as it was when the species was first identified in the US. When the weed grows on land, the stem thickens and competes with other riparian plants. Studies indicate that cattle graze on alligator weed, however native grasses are displaced as it has a proclivity to spread (Julien and Chan 1992). As the weed grows along shorelines and expands, the ability to travel along rivers declines because the navigable surface area diminishes. The weed causes sedimentation as it attaches itself to the shoreline, thereby increasing the amount of suspended solids in the water.

The weed is difficult to control as it can persist in several different types of environments. Biological, chemical, and mechanical control are the main methods of eradication. The introduction of insects the feed on the weed is the most common method utilized to mitigate growth. Mitigation of alligator weed along the banks of the SMR is undergone usually through manual removal. Organizations such as SMRF conduct river cleanups where invasive species mitigation is emphasized, however *Eichhornia* is the predominate species targeted (Guadalupe Blanco River Authority 2013) over other invasives, such as alligator weed.

Biocontrol agents such as certain species of beetle (Buckingham 1996; Julien and Chan 1992; Lu, Zhao, Ma et al. 2012; Schooler, Baron, and Julien 2006; Vogt, McGuire, and Cushman 1979), moth (Julien, Sosa, Chan et al. 2012), competitive flora (Cao, Wang, Xiao et al. 2014), thrip, butterfly (CABI 2019), and pathogen (Barreto and Torres 1999; (Gilbert, Auld, and Hennecke 2005) have been observed to mitigate alligator weed growth. Japanese hop has shown to provide competition to alligator weed and mitigate its spread. Biological control was first tested in the 1960s using different species of moth and beetle (Julien, Sosa, Chan et al. 2012; Spencer and Coulson 1976). Biological control methods can become an additional issue as introduced species sometimes feed on non-target plants.

Mechanical equipment is used to uproot the weed and shred the stems. The problem with mechanical removal is unless the entirety of the weed is removed, a single node can sprout roots and begin to regrow. Mechanical control can sometimes exacerbate alligator weed growth (CABI 2019) as remaining fragments can float downstream and recolonize.

Several herbicides are used to mitigate alligator weed growth (Table 5). Metsulfuron and dichlobenil have been tested and succeed in eradicating the weed's growth, however both lack selectivity. Glyphosate over water has also shown to mitigate growth (Sainty, Mccorkelle, and Julien 1998). Selective herbicides, such as metsulfuron and triclopyr triethylamine, show sustained results in reducing alligator weed accumulation and biomass (Schooler, Cook, Bourne et al. 2008). Several chemical control methods do not result in sustained reduction of the weed (Sainty, Mccorkelle, and Julien 1998). As such, chemical control is sometimes ineffective if it isn't paired with another control method or undergone using selective herbicides. Using herbicides directly on the weed eliminates the exposed portion of the weed, however the roots systems stay intact.

Manual removal is labor extensive and complicated as ensuring the entirety of the weed is removed can be difficult. However, it may be effective in removing small patches (Tanveer et al. 2018).

As an aquatic and riparian pest, the positive applications of alligator weed should be evaluated. Among these applications include medicinal applications, use in wastewater treatment, agricultural use, and biofuel production.

The weed is useful as a component in fertilizers due to its high potassium (K) content. Alligator weed can have as much 9.75% K in dry matter form (Hu et al. 2015). Combining alligator weed with nitrogen and phosphorus produces a fertilizer that is rich in nutrients and beneficial for plant growth. Table 1 contains the nutrients found in alligator weed. Within the stems and leaves the potassium amount falls between 4.9-9.75% and 1.4-1.92% within the roots (Dujing, Jianan, Keqin et al. 1987). The stem, leaf, and root samples from the study conducted by Dujing, Jianan, Keqin et al. (1987) to calculate the potassium content of alligator weed were harvested in both aquatic and riparian systems. The weed has been used in "green manure", manure comprised of plants and plowed back into the soil, to increase the amount of soil nutrients, like iron, zinc (Ye, Jiang, and Xu 2006), phosphorous, nitrogen, and potassium (Dujing, Jianan, Keqin et al. 1987), and improve zinc and iron uptake by plants.

Alligator weed has been tested in the removal of tartrazine (Gautam, Gautam, Banerjee et al. 2015; Gautam, Shivapriya, Banerjee et al. 2020), a light orange dye used commonly in textiles, malachite green (Wang 2010) and alizarin red S (Gautam, Shivapriya, Banerjee et al. 2020) through adsorption experiments that utilized the activated carbon of the weed and as a component in plant biomass. Although most productive in acidic environments (pH ~2.0), the weed proved to be a successful candidate as a replacement for commercial activated carbon in the removal of tartrazine in aqueous solutions (Gautam, Gautam, Banerjee et al. 2015). Through using an absorption technique to evaluate the propensity of the weed in simulating activated carbon, the significance of reusability and cost effectiveness was realized. The prevalence of alligator weed makes it a frugal alternative to activated carbon and a cost-efficient agent in the treatment of wastewater. Along with being a successful agent in the removal of dyes and improving water quality, biomass from alligator weed can be utilized in the fabrication of nanoparticles for carbon capture (Singh, Bahadur, Mee Lee et al. 2021). Biomass from plants is a source of cheap organic carbon which can be used in a variety of applications.

The biomass produced from alligator weed is a potential component in biofuel production. The weed can duplicate to weigh over 7.5 tons/hectare (Capareda 2019), thus enabling it to be harvested for biofuel production on a regular, frequent basis. Table 2 contains the cellulose content of alligator weed. The moisture content of the weed once harvested makes it a useful component in the anerobic digestion process in the production of biogas as well. Post anerobic digestion process, alligator weed has shown to produce over 4 liters of biogas (65% methane and 35% carbon dioxide) per kilogram (Capareda 2019).

The leaves of alligator weed possess phenolic capabilities. Five major phenolics (chlorogenic acid, salicylic acid, ferulic acid, kaempferol, and syringic acid) were identified within samples of alligator weed in vitro systems (Bhattacherjee, Ghosh, Sil et al. 2014). Phenolics are a class of naturally derived metabolites with anti-inflammatory, anticancer, antimicrobial, and antioxidant benefits (Mark, Lyu, Lee et al. 2019). The prevalence and perennial nature of the alligator weed leads it to be a quickly replenishing resource to be utilized in the isolation and extraction of phenolics.

Water lettuce (*Pistia stratiotes)*

Figure 20: *Pistia stratiotes* formed in the San Marcos River.

With African origins (Shapovalov and Saprykin 2016), water lettuce, *Pistia stratiotes* (Figure 23), is the most widely distributed hydrophyte in the world (Holm, Plucknett, Pancho et al. 1977). The first account of water lettuce in the US was during the 18th century in Florida (Dray and Center 1992). From there, water lettuce has spread to every state between Texas and Florida and into California. water lettuce is also found in the northern US and along the east coast (USGS 2021). As one of the world's worst weeds (Holm, Plucknett, Pancho et al. 1977), many southern states have prohibited intentional growth and it is considered a noxious species in South Carolina and Delaware (Dray and Center 1992). water lettuce is a pest due to its high prevalence within freshwater, but not necessarily due to the damage that it causes. In the US, production and hydroelectricity generation are not affected by water lettuce growth (Napompeth 1990). However, *Eichhornia* does obstruct irrigation flow (Dray and Center 1992) and some recreational activities. water lettuce accumulates sediment and debris from the shoreline and other plants and forms sudds, or dense accumulations of vegetation and debris along the surface (Holm, Plucknett, Pancho et al. 1977). water lettuce can be observed in many areas along the SMR. This plant can be found growing near other invasive aquatic plants, such as *Eichhornia* and elephant ear.

This perennial, free-floating plant is light green in color with tan-yellow roots. The roots are very fibrous and vary in size from 2-7mm in diameter and can grow up to 1m long (Holm, Plucknett, Pancho et al. 1977). The roots are similar to that of *Eichhornia* in that they appear very feathery. The leaves are oval or wedged shaped and grow very closely to each other in a rosette from short stems, pointing upward. As many as 15 secondary rosettes can be connected to one plant and each stem can carry up to 4 rows of rosettes (Dray and Center 1992). The leaves appear furry to the touch as they have small basal hairs along the base of some leaves. The stems are noticeably short in length and are typically unable to be seen from observation along the surface because the leaves grow so compactly from the plant. The pale white or green flowers of water lettuce are hard to find because they grow within the foliage (Dray and Center 1992). As the name implies, water lettuce generally looks like a head of lettuce on the surface of water.

The population of water lettuce spreads primarily through vegetative propagation (Dray and Center 1992) as long stolons connect the mother plant to daughter plants (Holm, Plucknett, Pancho et al. 1977). The viability of the seeds to produce more plants is dependent on the country which the water lettuce grows. In Africa, it spreads through seeds along with asexual reproduction (Holm, Plucknett, Pancho et al. 1977), however in the US, seeds causing population growth are not as common as asexual reproduction.

Some accounts report that water lettuce does not produce seeds in the US (Dray and Center 1989). Asexual is the main method of dispersal, possibly due in part to a lack of potential pollinators of the plant. When water lettuce grows flowers, the transition from bud to flower takes about 8 days. Once the flower has bloomed, it withers and falls after 2 weeks. Seed production of the flower varies depending on location. In the US, flowers typically produce up to 1 seed. The seeds will float along the surface until they become saturated with enough water to sink to the river bottom and germinate. According to Holm, Plucknett, Pancho et al. (1977), a seedling will appear on the surface within 5 days after the seeds have become saturated.

Water lettuce is a perennial, mat-forming aquatic pest that inhibits water flow and sunlight from reaching below the surface. It acts as a mat for many organisms, including mosquitoes and suspended particles. It can grow in slow or stagnant water, within vegetation debris, and along riverbanks. When water becomes more rapid or the water lettuce mat is moving, the mat will travel like a floating island to other sections of the river. Some environmental impacts of water lettuce are very similar to that of *Eichhornia* (Holm, Plucknett, Pancho et al. 1977). Mats formed by water lettuce become dense and inhibit sunlight from reaching below, water lettuce poses a threat to water levels due to added evapotranspiration, and it threatens native flora through competition for resources. Water lettuce has a narrow pH variance, growing only in water around 4 pH (Holm, Plucknett, Pancho et al. 1977). Water lettuce can lower pH and dissolved oxygen levels which can negatively impact fish populations (Grodowitz, Johnson, and Nelson 1992). Recreationally, navigation is difficult in areas of dense growth.

The use of chemicals to control water lettuce growth is often difficult, so biological control methods are most common. Due to its size, it is easier to move in large quantities compared to other invasives. Biological control methods have shown to be the most successful in mitigating water lettuce growth and surface area. Within the SMR, several organizations such as the San Marcos River Foundation and the San Marcos Greenbelt Alliance use kayaks to paddle out to areas of water lettuce growth and remove them by hand.

Several biological control methods have been used to mitigate water lettuce growth. Weevils have been used to reduce growth (Cordo, Deloach, and Runnacles et al. 1978; Grodowitz 1992) and their addition to aquatic environments results in increased levels of dissolved oxygen and populations of native microorganisms (Coetzee, Langa, Motitsoe et al. 2020). Studies on the biological control agent from Australia, N. affinis, indicate that the agent results in steady water lettuce decline. Of the three reservoirs studied with WL, N. affinis reduced WL populations by 80-100% (Grodowitz 1992). Native herbivores in TX, such as *Samea multiplicalis*, feed on water lettuce, leaving the weed with several holes within its leaves. Although some native species feed on the invasive plant, significant population decline does not occur solely from the herbivorous organisms (Grodowitz 1992). Additional biological control agents such as moths, native weevils, and the Australian weevil, N. affinis, can be used to intensify reduction. Upon observation, growth within the SMR seems unobstructed by native herbivores. However, competition with *Eichhornia* or alligator weed does seem to decrease the rate of water lettuce growth.

When floating invasive plants become saturated with water (>90%), a mat can weigh up to 500 tons per hectare. Surface area doubling time can be a little as a few days (Howard and Harley 1997). Large machinery, such as bulldozers, can be used to remove large quantities from waterways. For mechanical control to be efficient, the rate of removal must outpace the rate of regrowth. Also, as water lettuce mats are removed, individual weeds can be broken off and travel downstream. Precision is emphasized while using manual control while mechanical control can remove a larger amount in less time.

Historically, the usage of herbicides has been unsuccessful in mitigating growth so biological control became the predominant method. Since the early 1900s, chemical control has been utilized to mitigate the growth of aquatic invasive weeds. The most common herbicides used to reduce water lettuce growth are glyphosate and diquat (Table 5) (Howard and Harley 1997). Chemical control is most productive in areas with smaller growth rather than larger ones. Also, unintended problems arise as non-target species are impacted by the chemicals applied. Howard and Harley (1997) state that chemical control may not be the best method of mitigating aquatic weeds because the seeds are not targeted. Applying chemicals can also affect recreation as it inhibits recreational usage of an area until the chemicals have been safely diluted over some time. The natural flow of water results in less soakage of chemicals into the targeted invasive plant as well.

Manual control can be undertaken easily. Each individual weed does not become too saturated with water so their removal by hand is not strenuous, however removal can be time consuming especially in areas of high density.

There are several methods of upcycling invasive water lettuce. Applications include phytoremediation, and medicinal and agricultural use. It can be added during the aerobic composting procedure to increase the phosphorous content of soil (Abdul, Jinna, and Ali 2012; Kanwal, Iram, Khan et al. 2011). Fertilizers containing phosphorous can be costly so adding water lettuce is a frugal alternative that meets the same result. Combining invasive plants to composting mixture benefits the environment in several ways: the invasive is being removed from an ecosystem, and rather than adding chemicals to increase nutrient levels of soil, a natural source is being used. Emphasis on the ability of invasive plants to add needed nutrients to compost should increase.

Water lettuce is a suitable candidate to use for phytoremediation as suspended solids stick to its roots (Lu, He, Graetz et al. 2010; Rao and Reddy 1984). Macro and microparticles can be removed by the plant and ethyl extracts negatively effects algae growth (Aliotta, Monaco, Pinto et al. 1991). It has been found that the metal concentration in detention ponds is reduced by water lettuce as the particles get absorbed into the roots. It accumulates Cr, Fe, magnesium (Mn), Ni, Pb, Zn, and Cu very quickly (Lu, He, Graetz et al. 2011), along with ammonium and nitrate-nitrogen ((Nelson, Smith and Best 1981). Absorbed particles most likely stay within the roots and do not transport within the shoots of the plant. Landfill leachate is successfully removed by water lettuce (Abbas, Arooj, Ali et al. 2019). Abbas, Arooj, Ali et al. (2019) found that when paired together. Many studies indicate the effectiveness of both water lettuce and *Eichhornia* in wastewater treatment (Akinbile and Yusoff 2012; Qin, Zhang, Liu et al. 2016). The combination of these weeds poses severe environmental harm, but also poses as a successful duo in phytoremediation.

Water lettuce has been used in medicinal applications (Gillet, Dunlop, and Miller 1988; Holm, Plucknett, Pancho et al. 1977). The leaves of water lettuce are found to have a high Vitamin A, B, and C content and have been used to treat leprosy, eczema, and syphilis in some countries. Table 2 contains the nutrients found in water lettuce. It also exhibits diuretic, antifungal, and antidiabetic properties (Aasim, Karatas, Khawar et al. 2013). Medicinal applications of WL have not been studied as extensively in the US compared to other countries.

Elephant ear (*Colocasia esculenta*)

Figure 21: *Colocasia esculenta* in the San Marcos River.

Elephant Ear, *Colocasia esculenta* (Figure 24), also known as wild taro or taro, is a member of the Arum Family (Aracea) (Kaushal, Kumar, and Sharma 2015) and can be found along several banks of the San Marcos, Colorado, Guadalupe, Blanco and Comal River (Akridge and Fonteyn 1981). This plant is often overlooked as a harmful invasive because of its prevalence in TX. Elephant ear is polymorphic and uncertainty surrounds its genetic and geographic origins. However, the plant is believed to have originated from southern India and southeastern Asia (Ahmed, Lockhart, Agoo et al. 2020; NC Extensive Gardener 2021; Rashmi, Raghu, Gopenath et al. 2018). Prior to the global exchange of goods, Elephant ear was the most predominant food crop and likely played an important role in the agricultural revolution (Grimaldi 2016; (Grimaldi, Muthukumaran, Tozzi et al. 2018). It exhibits geographical variance and occurs in varying forms such as *Xanthosoma sagittifolium*, *Cyrtosperma chamissonis* (giant swamp taro), *Alocasia macrorrhiza* (giant taro), and *Colocasia esculenta* (Kaushal et al. 2015). In TX, two taxonomic varieties are present: C. esculenta var. esculenta and C. esculenta var. antiquorum (Moran and Yang 2012) but can be differentiated by the size of the corm, the beginning of the roots system that holds the roots in place. Elephant ear was introduced into the SMR in the 1900s (Atkins and Williamson 2008; Akridge and Fonteyn 1981) and records indicate it has been actively present in TX since 1929 (AustinTexas.gov 2016). It was first introduced into the US likely during human migration (Chaïr, Traore, Duval et al. 2016), however the precise mode of its invasion of US waterways is unknown.

Elephant ear is a perennial herb and can grow up to 1-3 meters tall (Atkins and Williamson 2008; Rashmi, Raghu, Gopenath et al. 2018). A long petiole grows from the central corm which grows just below the soil surface. From the petiole, a large leaf grows in a rosette. The petiole and leaves are connected at the center of the leaf. From there, large visible veins grow along the spine of the leaf and reach out, extending almost to the edge of the leaf. Prior to leaves forming, they appear in a rolled unexpanded form. The leaves of elephant ear can vary in color with some a light or dark green, greenish purple, or in combinations of light pink, light red, and green (Rashmi, Raghu, Gopenath et al. 2018). The leaves are comprised of two sections, the intercostal lamina and large veins (Stein, Strauss, and Scheirer 1983). Along the SMR, the leaves are a rich green color and can grow up to 60cm in length and 35 cm in width (Atkins and Williamson 2008). The roots are very fibrous, and the corm is often irregularly shaped. The roots do not extend far beyond the corm, making it easily extractible by hand. The corm is commonly oval-shaped, however inconsistencies in bumps or shapeliness are normal.

There are over 200 varieties of elephant ear worldwide. As mentioned, the plant exhibits high variability depending on geographic location. Genetic diversity is likely caused during sexual reproduction of the plant. Genetic diversity caused by sexual reproduction is only present in Asian countries, and not among those found in Africa and the US. Clonal, or asexual, reproduction is most common in Africa and the US (Chaïr, Traore, Duval et al. 2016). The plant can spread through propagation or from seeds. A mother plant will produce several underground corms which can be dug up and broken apart to produce more elephant ear. Propagation techniques are used in countries where elephant ear is commodified and acts as a staple crop.

Along the SMR, elephant ear spreads through asexual division. Once a mother plant develops corms, petioles will begin to sprout. Similar to *Eichhornia*, mother plants will spread by growing daughter plants. Unlike *Eichhornia* that connects to daughter plants through a stolon, elephant ear grows daughter plants through corms. The plant spreads during flooding events as well. Entire plants or just the corms can be dislodged from the ground and be transported downstream. Once reburied, elephant ear will sprout and continue displacing native flora. In the SMR, the most common method of spreading is during flooding events or asexual reproduction.

Elephant ear affects riparian and aquatic communities as it limits areas of growth and displaces native vegetation growing along the shoreline (Atkins and Williamson 2008). It can densely populate areas along the river and outcompete native plants (Nelson and Getsinger 2000). Excessive growth of the plant can cause waterways to narrow and in extreme cases inhibit recreational activities due to overgrowth. As the SMR is home to many endangered species, such as Texas wild rice, the mitigation of invasive species like elephant ear is critical to ensure native species are not outcompeted by non-native, invasive plants. Studies show that the presence of elephant ear leads to declines in native flora (Atkins and Williamson 2008). Habitat suitability for endangered and native species decreases as the elephant ear population increases.

Several control methods have been employed to manage the growth of elephant ear. Atkins and Williamson (2008) studied 6 blocks of elephant ear growth along the SMR to measure the effectiveness of various techniques that could be used to mitigate growth. They concluded manual control is the most effective at removing the plant, however other methods such as chemical and mechanical could also be utilized.

Studies on the effectiveness of biological control in mitigating populations along the SMR have not been conducted, however it has been observed that the plant hopper, *Tarophagus colocasiae*, does cause dieback. The specialist species feeds solely on elephant ear. The plant hopper congregates along the leaves and feeds on the leaf and petiole. The plant hopper feeds on the petiole along with laying eggs on the inside (Diaz, Manrique and Valverde 2021). Biological control agents from the SMR have not been studied.

Mechanical control has shown to be ineffective. Shoreline displacement and erosion can be caused by mechanical control techniques. Also, because elephant ear primarily reproduces asexually along the SMR, if the corms stay intact below the soil surface, regrowth will occur even after mechanical control has removed the leaf and petiole. To ensure the entire plant is removed, the corms need to be dug out from the ground.

Herbicides are applied to mitigate its growth. Herbicidal applications have shown to decrease leaf coverage and are most effective when combined with manual control techniques. Chemical control has shown to not have a large effect on the soil bed or cause as much riverbank erosion as manual control (Atkins and Williamson 2008). Herbicide applications of glyphosate, triclopyr, and 2, 4-D aid in control EE spread (Table 5). However, diquat, glyphosate, triclopyr, and 2, 4-D cause plant injury. Plant recovery after diquat application takes longer than that from the other three pesticides, but diquat does not affect the entirety of the plant. Underground plant tissues can regrow after diquat is applied (Nelson and Getsinger 2000). Because endangered flora grows closely to elephant ear along the SMR, the application of herbicides is not the most preferred method. Non-target species are often adversely affected through indirect contact with herbicides.

Manual removal is the most effective method of mitigating growth. The corms can be pulled from the ground by hand or using a shovel. Atkins and Williamson (2008) discovered that both manual and chemical control result in a greater decrease in leaf cover than mechanical removal. Manual removal may be the most effective at removing weeds and unwanted plants, however it is the most time consuming and physically exhaustive. In the case of elephant ear, manual removal results in the largest decrease in leaf coverage compared to chemical and mechanical control.

Predominantly, elephant ear is consumed for its nutritional benefits. In many countries, elephant ear is farmed because it serves as a staple crop. Other applications include phytoremediation, biofuel production, and making biodegradable films (Briones, Jazmin and Pajarillaga 2015).

Elephant ear is a good source of carbohydrates and is a staple food in many tropical and subtropical countries such as Bangledesh (Hussain, Norton and Neale 1984), Cameroon, and several other African countries (Kaushal et al. 2015). Corms have more than twice the amount of carbohydrates at potatoes (Rashmi, Raghu, Gopenath et al. 2018). The corms contain up to 70-80% starch and is a source of iron, phosphorous, riboflavin, B6, vitamin C, and K (Table 2) (Rashmi, Raghu, Gopenath et al. 2018; Le Quach, Melton, Harris et al. 2000). The cell wall contains monosaccharides and polysaccharides (Le Quach, Melton, Harris et al. 2000) which, when consumed, provide the cells with short term energy. Elephant ear is commonly grown in many countries for its underground corm, vegetables, and root (Rashmi, Raghu, Gopenath et al. 2018). The corm contains the bulk of the nutrient content and can be prepared in a variety of ways for consumption. During preparation, it is important to reduce the acridity factor, or pungency level, prior to consumption. Methods of decreasing acridity include peeling, fermentation, or soaking during processing (Kaushal et al. 2015). The high acridity can cause throat and nasal irritation and is caused by the calcium oxalate present in some corms. According to Rashmi, Raghu, Gopenath et al. (2018), it is the 9th most cultivated crop in the world. In the US, agricultural usage of is uncommon. Most attention is regarding its mitigation.

Elephant ear can be used as an agent in phytoremediation to remove metals such as Pb and Cd in low concentrations. The metals accumulate mostly in the root system indicating that the metals do not translocate to the leaves when present in small quantities. When large quantities of Pb and Cd are present, the leaves turn yellow and the roots decay. In smaller quantities, elephant ear does not change in visible appearance, however the number of roots increases. Higher concentrations of some metals reduce the chlorophyll content and its biomass (Bindu, Sumi, and Ramasamy 2010). The plant increases the dissolved oxygen content in wastewater treatment applications, which can lead to a decrease in the chemical oxygen demand of humic substances and other bulk organics. Changes in the pH of water from sewage being added during wastewater treatment damage the root system and lead to less uptake of waste (Bindu and Ramasamy 2007). Moreover, using elephant ear in combination with other plants is a frugal means of improving water quality through the removal of some metals.

The glucose in elephant ear can be utilized to make bioethanol (Biofuels International 2017; Wu, Hung, Lo et al. 2016) through the fermentation process. According to Biofuels International (2017), biofuel has been produced from elephant ear by extracting the oil from the plant and fermenting it for several weeks. The fuel derived from the fermented oil is as effective as petroleum products used for automobiles (Hanaki and Portugal-Pereira 2018). Using saccharification and liquefaction, 100 g/L of glucose can be obtained from 170 g/L of elephant ear waste (comprised primarily of the peels). Fermentation in a bioreactor can then produce ethanol from the elephant ear. Biofuels reduce the consumption of fossil fuels and are carbon neutral (Hanaki and Portugal-Pereira 2018). Generating liquid fuel from crops, specifically invasive species, is a sustainable method that can aid in meeting the needs of the present population without inhibiting future generations of meeting their needs. Table 2 contains the cellulose, hemicellulose, and lignin content of elephant ear.

Many tuber crops are used as anti-inflammatories and to reduce the risk of many cancers. Elephant ear contains bioactive molecules that effectively counter carcinogenic agents, pathophysiological processes such as stress and inflammation, and boost the immune system (Ribeiro Pereira, Bertozzi De Aquino Mattos, Nitzsche Teixeira Fernandes Corrêa et al. 2020). Elephant ear is also used in pharmaceuticals to treat depression and anxiety (Kalariya, Parmar, and Sheth 2010). The combination of polysaccharides, glycerol, and antioxidants within the corm are very beneficial medicinally and can be used to treat or alleviate many physiological and medical ailments.

The starch can be utilized to make biodegradable films like that of plastic. Higher concentrations of starch content results in more durable films whereas less starch gives the biodegradable film higher flexibility (Briones, Jazmin, and Pajarillaga 2015). Biodegradable films derived from starch can reduce plastic use. The high starch content of elephant ear has also been utilized in cotton printing. Modified starch can be used as a thickening agent and poses as a more environmentally friendly alternative to synthetic dyes (Mongkholrattanasit, Klaichoi, Rungruangkitkrai et al. 2021). Color fastness and resistance are maintained when using elephant ear instead of synthetic dye materials.

APPENDIX D: HYDROGEL USAGE AND PRODUCTION

Hydrogels, or aqua gels (Dahman 2017), are a water-swollen polymeric object that reach a gelatinous orb-like structure through a combination of or an individual occurrence of the cross-linking of covalent bonds or hydrogen bonds, hydrophobic interactions, the crystallizing of polymers, ionic interactions, or bio-recognition interactions (Peppas and Hoffman 2020). Water acts as the medium at which the polymers are distributed throughout the hydrogel. The characterization of hydrogels is based upon the individual size of each hydrogel, absorption capabilities, degradation rate, and other physical parameters (Catoira, Fusaro, Di Francesco et al. 2019).

Synthetic polymers, which are molecularly engineered to be absorptive and maintain structure, or natural polymers, derived from naturally occurring substances such as polysaccharides or proteins, are used to produce hydrogels. Polymeric hydrogels are a viscoelastic structure that swells when introduced to aqueous substances and are not water soluble (Laftah, Hashim, and Ibrahim 2011). Biomedical applications of hydrogels include tissue engineering (Dahman 2017; Kalaf, Flores, Bledsoe et al. 2016), medicine delivery, contact lenses, and in healthcare products (Catoira, Fusaro, Di Francesco et al. 2019; Peppas and Hoffman 2020, Sannino, Demitri, and Madaghiele 2009).

Hydrogels can also be used in environmental applications such as wastewater treatment for their ability to absorb aqueous pollutants such as heavy metals and dyes (Thakur, Sharma, Verma et al. 2018). The malleability and absorbency ability of hydrogels make it a favorable addition when producing products that need to be lightweight and durable while also having high absorptive ability. Hydrogels are comprised of one of three polymer chains: synthetic, semi-synthetic, and natural.

Synthetic polymers

Synthetic polymers are those that are bioengineered to achieve desired results and exhibit more durability and longevity than natural hydrogels. Synthetic polymers are often used as these materials are cheaper, can be produced in large quantities faster, and have a longer shelf-life than natural polymers (Alves, Morsink, Batain et al. 2020). They are usually built from acrylamides, acrylates, or other petroleum-based monomers (Liu, Wang, Li et al. 2017; Mignon, De Belie, Dubruel et al. 2019; Nesrinne and Djamel 2017).

Semi-synthetic polymers

Semi-synthetic polymers are often cellulose based. Semi-synthetic polymers include proteins, polysaccharides, and polyesters. The limitations of natural polymers (those derived from proteins, cellulose, or polysaccharides) are addressed through modification of the polymer (Macchione, Aristizabal Bedoya, Figueroa et al. 2021). This modification is what sets the distinction natural and semi-synthetic polymers. Although naturally derived, these polymers are considered semi-synthetic due to the source material being modified prior to the development of hydrogels.

Natural polymers

Natural hydrogels are those derived from biological material such as plants, proteins, and polysaccharides. Natural hydrogels are favorable in biomedical applications due to their biodegradability and usage of recognizable biological material (Madduma-Bandarage and Madihally 2021). Natural polymers include those derived from proteins such as collagen or elastin, or those derived from polysaccharides such as starch, xanthan, alginate, chitosan, among others (Catoira, Fusaro, Di Francesco et al. 2019; Peppas and Hoffman 2020). They are safe, biocompatible, and are used in many applications including cosmetics (Alves, Morsink, Batain et al. 2020), medicine delivery (Catoira, Fusaro, Di Francesco et al. 2019), wound healing (Ehterami, Salehi, Farzamfar et al. 2020; Kalaf, Flores, Bledsoe et al. 2016), and in sanitary products (Sannino, Demitri and Madaghiele 2009).

Superabsorbent polymers (SAPs)

Polymer hydrogels, produced with a cross-linker and solvent, that absorb and retain large quantities of water or biological fluids have been given the denomination superabsorbent polymer (SAPs) (Laftah, Hashim and Ibrahim 2011). SAPs differ from hydrogels in that they present a higher ability to absorb liquids (up to 1000 times their weight whereas hydrogels absorb up to 10 times) due to their lower cross-linking degree (Mignon, De Belie, Dubruel et al. 2019). SAPs have drastically improved the absorption capacity of sanitary products (Bae, Kwon, and Kim 2018) and are often a frugal addition to also increase durability, functionality, and offer eco-conscious disposal methods when using natural polymers. Synthetic materials can be used when fabricating SAPs, however natural polymers such as proteins and polysaccharides have shown to rival that of synthetic polymers (Tu, Yu, Chen et al. 2017; Mignon, De Belie, Dubruel et al. 2019; Thakur, Sharma, Verma et al. 2018). When using natural materials versus synthetic materials, which are often petroleum-based, the potential risks associated with dermal contact with hazardous chemicals decrease. See Table 6 for the dermal contact associated with each layer of a menstrual pad.

Menstrual products commonly use SAPs within the absorbent core layer to increase absorbency. Synthetic polymers such as acrylate or acrylic acid are most commonly used in conventional pads (Kiatkamjornwong 2007). However, synthetic materials pose health risks to users. In the US, menstrual products are regulated by the Food and Drug Administration as a Class I Medical Device (Code of Federal Regulations 884.5425 and 884.5435), however this regulation is not legally enforceable thus acting as a general guide or recommendation for manufacturers to voluntarily follow (Bae, Kwon, and Kim 2018). It is recommended that the chemicals and additives be communicated to the consumer, however this is not required. A premarket submissions guideline, 510(k), provides suggestions and recommendations to manufacturers to test the health effects from dermal contact and the biocompatibility of menstrual pads in accordance with ISO-10993 (Biological Evaluation of Medical Devices Part 1: Evaluation and Testing) (Bae, Kwon, and Kim 2018). Again, however, these are non-enforceable.

SAPs derived from natural polymers allow for biodegradation, biocompatibility, are less costly, and pose less health risks compared to those derived from synthetic polymers. To fabricate compostable menstrual pads, SAPs derived from natural polymers must be used. Using SAPs rather than hydrogels increases absorbency without increasing weight or losing flexibility and durability. The SAPs act as the superabsorbent core of the menstrual pad and is the site where liquids are stored once absorbed.

Table 6: Dermal contact associated with a menstrual pad using SAPs

1	Top sheet	Direct dermal contact
2	Acquisition Layer	Indirect dermal contact
3	SAP core	
4	Back sheet	Little exposure
5	Adhesive	

Incorporating hydrogels or SAPs within the core layer of the pad increases absorbency while also supporting flexibility, structural integrity, and comfort. Prior to the use of SAPs in FHPs, liquid absorbed was held within the spaces between cellulose fibers extracted from wood. With this method, increasing absorbency was undergone by thickening the absorptive layer itself, resulting in a very thick product (Buchholz 1996). Once SAPs were incorporated into FHPs, the size and bulkiness decreased as the pad itself became slimmer. SAPs increased absorbency and made the pads more convenient and discreet.

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