MantaRay: A Novel Autonomous Sampling Instrument for *In Situ* Measurements of Environmental Microplastic Particle Concentrations

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***Abstract*— Presented here is the initial hardware and software design of a prototype autonomous microplastic sampling instrument. Microplastics are defined as particles of plastic < 5 mm greatest dimension. They are becoming pervasive in the world ocean due to anthropogenic pollution. The ocean has spatially variable concentrations of surface microplastics, so attempting to identify trends in global dispersal patterns is difficult and expensive using current research techniques. Understanding the global dispersion patterns and degradation rates of microplastics will help to uncover the associated human and ecosystem impacts. A novel low-cost oceanographic sensor has been developed that can determine the concentration of marine microplastics over large spatial areas. This sensor can remove plastic particulates from seawater and archive them for later analysis, determine microplastic concentrations for 28 discrete samples recording GPS position, and simultaneously measure salinity and water temperature. This sensor has been designed around the open-source Arduino platform, allowing for maximum implementation of additional sensors and systems in future prototypes. The MantaRay sensor can be implemented on a drifter, mooring, or Autonomous Underwater Vehicle to gather diverse data on the dispersion of microplastics. This sensor could drastically cut research costs associated with studying deep-sea microplastic concentrations and increase our understanding of plastic dispersion and degradation rates in marine ecosystems.**

Keywords*— *microplastic; plastic; pollution; Arduino; sensors; MantaRay

I. INTRODUCTION

The growing amount of marine plastic debris in the oceans is a result of exponentially rising rates of industrial plastic production and the slow degradation rate of plastics in the environment. Unlike many other substances, plastics can take hundreds of years to break down and have only been produced on an industrial scale for about 75 years [1]. Microplastics are currently defined as pieces of plastic that are 5mm or smaller in diameter and are distinguished by their original use and their size. Primary microplastics begin their life cycle as small plastic particles and are found in the form of pre-production resin pellets used for plastic injection molding [2], exfoliants in cosmetic products [3], industrial abrasives, and synthetic fibers from textiles [4] to name a few. These small and lightweight plastics are easily spilled, blown away, and transported over great distances in river systems and in the ocean. Secondary microplastics begin their life cycle as larger plastic products (e.g. plastic containers, consumer products, and fishing gear) and are broken down into small fragments from ultraviolet radiation, wave action, collision with coastal landforms, and many other ways. Although many plastics sink into aquatic and marine sediments [5], certain buoyant plastic types (e.g. low-density polyethylene and polypropylene) tend to float on the surface and persist in the environment. These microplastics are carried by ocean currents and tend to accumulate in any of the five major ocean gyres that act as large-scale whirlpools for plastic pollution [6]. However, the exact pathways to these zones and the persistence of microplastics once they reach the ocean are largely unknown.

The size of these microplastics is of great concern because a wide range of marine organisms can potentially digest them, resulting in physiological problems. In the water column, plastic polymers have chemical structures that readily adsorb Persistent Organic Pollutants (POPs) from the water. For example, dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyls (PCB) can be adsorbed from the water column with polyethylene strips to determine contaminant concentrations [7]. Upon ingestion and subsequent digestion of microplastic particles by marine organisms, this process can be reversed and POPs can be transferred into tissue. For example, a seabird, the streaked shearwater *(Calonectris leucomelas*) was shown to readily uptake PCBs in their fatty tissue from the digestion of contaminated microplastics [8]. Laboratory studies have also shown that fishes [9] and marine worms [10] will uptake organic pollutants upon digestion of contaminated microplastics. These pollutants can bioaccumulate through predatory marine organisms and may eventually biomagnify through trophic levels to humans with sufficient dietary exposure. Plastic particles can also obstruct digestive tracks in

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filter feeding organisms like mussels [11] and corals [12], leading to starvation, reductions in energy, and mortality in the organisms. Other studies have shown that microplastics are creating a novel unique ecological habitat, called the "Plastisphere", for opportunistic pathogens and distinct bacterial communities in the open ocean [13].

Presently, scientists have a difficult time estimating the vast amount of plastic pollution entering the ocean, with estimates ranging from 4.8 to 12.7 million metric tons of plastic dumped into the ocean annually [14]. Without a good understanding of dispersal ability and concentration of microplastics, it is hard to make correlations to other parameters such as fish and marine mammal mortality, transportation of organic pollutants, and general ecosystem and human health in areas impacted by microplastics. Current marine microplastic sampling methods involve towing a neuston net behind a research vessel at sea, analyzing the microplastic particles that are collected, and calculating plastic concentration based on the volume of water that was sieved through the net during the sample time [15]. In order to sample the dangerous waters in the deep ocean, larger research vessels are needed, which can cost tens of thousands of dollars per day. The alternative is to automate this process with an array of robotic sensors and allow autonomous instruments to spend months at sea without the need for human intervention and costly time on research vessels.

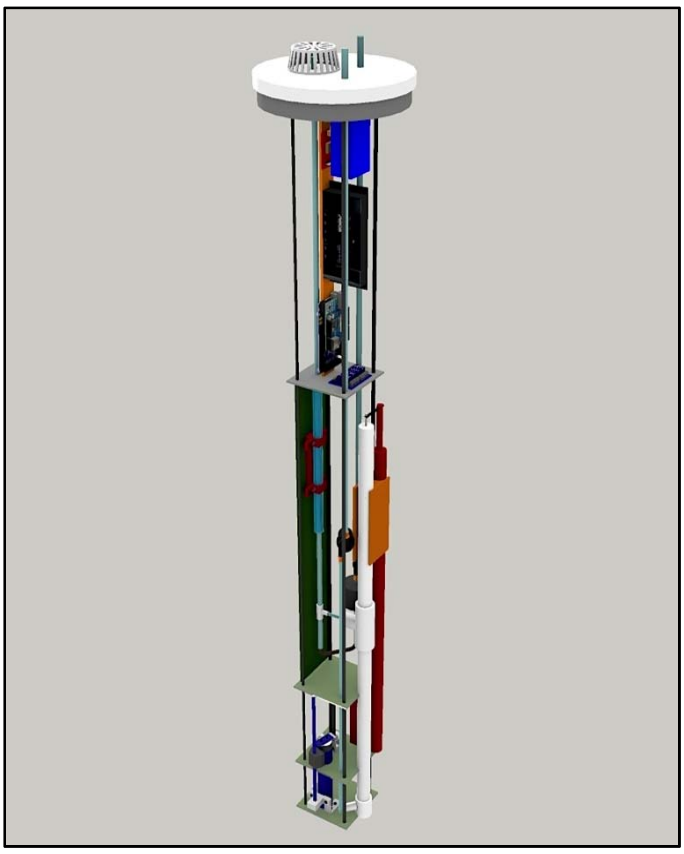

Fig. 1. MantaRay Sensor CAD Design

The MantaRay (Fig. 1) is a fully autonomous sensor capable of calculating marine microplastic concentrations over large spatial areas and archiving the microplastic particles for later analysis. The sensor uses a flow-through pump and filtration system to collect 28 discrete samples of customizable volume and can record GPS location, temperature, and salinity data at the point of sampling. The MantaRay sensor was built around the open-source Arduino platform for USD $2,000. To better understand dispersal patterns and degradation trends, the MantaRay could provide insight into the types of plastics and concentrations that are found in different areas of the ocean. Ideally, a fleet of these instruments would be deployed in connection with one another to provide data for microplastic pollution dispersal models and other scientific correlations.

II. Mechanical Design

The MantaRay pressure housing (Fig. 2) is composed of an 8-inch PVC pipe with a bottom cap and a top cleanout adapter. The housing floats upright at the surface of the water column with ballast weight at the bottom of the housing and a buoy at the top to allow vertical orientation in the water. D-cell alkaline primary batteries that are used during deployment are factored in as partial ballast weight to achieve proper orientation. The intake for the MantaRay rests 30cm below the water line to ensure that the internal pump is not drawing air into the system, while still sampling in an area where surface microplastics are actively mixing and residing. A small plastic grate around the intake ensures that only small particles, and not larger biotic matter, enter the flow-through system for analysis. Protruding from the top of the pressure housing buoy is a small PVC tube that extends the GPS antenna vertically 80 cm in the air for increased signal reliability in rougher ocean conditions. In total, the entire drifter housing stands 3 m tall. Similar to other standard drifter floats, canvas wings were attached to the side of the housing to maximize the dispersal ability of the instrument by catching ocean currents. These canvas wings allow the instrument to move over great spatial distances during the 28-sample mission. As a drifting instrument, the MantaRay is better able to track and follow typical dispersal patterns of marine microplastics and discover accumulation zones.

In order to secure the instrument inside the pressure housing, the MantaRay was mounted to the underside of an 8-inch PVC cleanout plug, which securely screws into an 8-inch female cleanout adapter at the top of the pressure housing. The internal system components are built around four 1.25 m 1/4-20 threaded rods that are secured together with four 4-inch x 4-inch square PVC component platforms. All components used for sampling and processing are mounted directly to these four threaded rods, or mounted to one of the four component platforms spanning the length of the instrument. In order to accommodate for a changing prototype and incorporation of additional components, generic mounting boards were used that had a large grid of mounting holes.

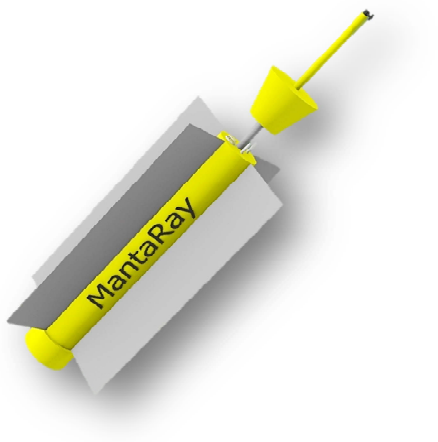

Fig. 2. MantaRay Drifter Pressure Housing CAD Design

III. Hardware Design

All MantaRay electronic and sensor components can be seen in Table 1. The MantaRay is based around a simple flow-through pump and filter system (Fig. 3). Water is pumped through the instrument from the ocean surface using a primary 12 V circulation pump and a series of ½-inch vinyl tubes. As water enters the instrument, it is pulled through an optical sensor for optical analysis of flow-through particulates. The optical sensor contains two 650 nm 150 mW lasers and two binary photodetectors positioned in line across a ½-inch glass flow tube. A break in either of the laser paths by a particle moving through the system creates a binary pulse in the photodetector that is interpreted by the microcontroller as a particle in the system. Component potentiometers were used to adjust the sensitivity of the optical sensor photodetectors to ignore background noise due to the opacity of seawater and bubbles that may enter through the flow-through stream. When the optical sensor detects no particles, the main pump freely and continuously pumps water through the system and out the exhaust. A 279 µm pore size SHURflo® strainer is positioned upstream of the primary flow pump to ensure it does not become clogged with any debris that may be missed by the optical sensor.

When the optical sensor detects a particle, a mechanical relay turns the primary flow pump off, and a secondary 12 V circulation pump is activated, diverting the flow through a secondary filtration system. With the primary pump deactivated and the secondary pump now on, the sample water containing the particle is forced through the filter column, which is a 76 cm long 1-inch PVC pipe containing one of 28 different 500 µm round stainless steel filters. These filters are oriented vertically on a 3/8-inch threaded rod at ½-inch spacing, ensuring that only one filter is exposed to the flow-through water during a given sample interval. The secondary pump remains on for 10 seconds, which allows sufficient time for the particle to be diverted into the filter column and trapped on the filter before the secondary pump shuts off and the primary flow-through pump is once again activated. With this process, any particle that enters the intake will be diverted onto a filter in the filter column, while particle-free water will be pumped through the instrument without entering the filter column. This active detection scheme continues until a predetermined volume of water has been pumped through the instrument. The MantaRay has the capability to repeat this process for 28 discrete samples of customizable volume, so point concentration measurements of particulate can be taken in the field.

After a sample has been completely collected, the filter column linear actuator is moved vertically to position a brand new blank filter in place for the next sample. The linear actuator has potentiometer feedback that allows for the very precise positioning (< 0.5 mm) of filters in the filter column. This way only one filter is ever exposed to the flow-through water at a time, ensuring discrete collection for a given sample. Before each sample is started, the Arduino interrogates an onboard GPS for a position reading. It simultaneously records water temperature, salinity, and temperature and humidity inside the pressure housing. A second GPS reading is taken at the end of each sample in order to determine the boundaries of a given volume of water sampled.

Between each sample, the internal flow-through tubing is cleaned with a small amount of disinfectant. An automated 60 ml syringe was designed using a 9 V high-torque motor connected to a lead screw. The syringe plunger is double mounted to a nut fixture on the lead screw as well as a guide

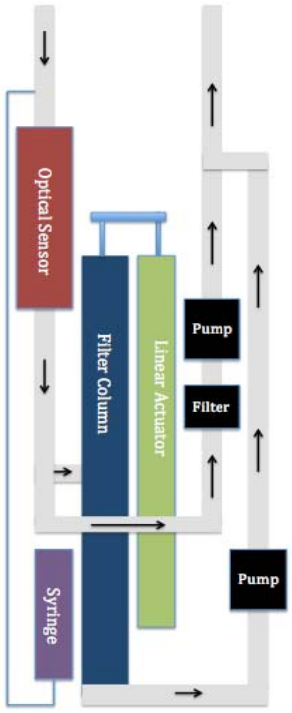

Fig. 3. MantaRay Flow-Through Hardware Diagram. Arrows represent direction of water flow.

TABLE 1: MANTARAY MAIN ELECTRONIC COMPONENTS AND SENSORS

System Component	Manufacturer	Part
Microcontroller	Arduino	MEGA
Motor Driver	RioRand	MOSFET IRF3205
SD Shield	RioRand	W5100
Humidity Sensor	wRobot	DHT11
GPS	Adafruit	GPS Breakout
Solar Charge Controller	Docooler	10A Controller
Relay Module	SainSmart	2-Channel Relay
Optical Sensor Detector	RioRand	Photodiode
Optical Sensor Laser	VentiSonic	KY-008
Temperature Sensor	Sunkee	DS18B20
Filter Actuator	Progressive Automations	(18 inch) PA-14P Linear Actuator
Syringe Motor	Hossen	12 V High-torque Motor
Flow Pumps	Huhushop	12 V Circulation Pump
Salinity Sensor	Custom PCB	LM741 Amplifier

rail to limit strain on the plunger and lead screw during the actuation process. A 60 ml syringe is filled with disinfectant before deployment and 2 ml of disinfectant is released after each sample near the intake. The flow-through pump pulls the disinfectant through the system and allows it to sit in the internal plumbing for 10 minutes before exhausting it from the instrument. Biofouling in the internal flow-through system could put strain on the flow-through pumps, block passage of particles in the system, and interfere with optical components, so the disinfectant process is necessary for a successful deployment.

All of the data during a given sample, including the number of particles that were detected, are written to an onboard SD card after each sample is completed. Upon recovery of the instrument after a deployment, the particle detection number recorded for each sample will be cross-analyzed to the contents of each individual filter to determine the actual number of plastic particles present compared to opaque organic matter that was also captured during a sample.

The MantaRay runs on a 12 V power supply both on the bench and during deployment. A series of voltage regulators are used from the main 12 V power supply to provide power to different modules involved with sampling. The Arduino board requires a 7.5 V power supply, both onboard circulation pumps require 12 V, and the linear actuator used for moving the filters requires 9 V. Although the MantaRay prototype does not currently use rechargeable batteries during deployment, a 10 A solar charge controller was incorporated into the hardware design for a future trickle charge module with a series of 12 V sealed lead acid batteries. This feature would allow longer deployments and the capacity to analyze more water per sample due to the relative power consumption of the onboard pumps and microcontroller. During a deployment of this prototype, standard D-cell alkaline batteries will be used in series to achieve the required 12 V input and necessary power requirements needed by the instrument. The biggest power consumption onboard the MantaRay comes from the circulation pumps, which draw around 325 mA during nominal usage and exhibit startup spikes approaching 500 mA. The circulation pumps have a 6.5 l/min flow rate, which is a limiting factor for water analysis during deployment. With this rate and power consumption, a typical deployment sample would actively analyze surface water for around 6 hours, resulting in a total volume of 2,340 l per sample. The Arduino microcontroller has been programmed to be as power efficient as possible, entering a sleep mode between samples that brings the overall current draw down to about 25 mA. During active sampling, the Arduino is providing power to the optical lasers, photodetectors, a relay module, a motor controller, a GPS, writing to an SD card, and is occasionally interrogating temperature, salinity, and internal humidity sensors, consuming a total 244 mA during sampling in addition to the pumps. The total power needed for a 28-sample deployment adjusted for optimal voltage and temperature compensation is therefore 1.4 kW•hr.

IV. SOFTWARE DESIGN

To control the various sensors, motors, actuator, relays, and pumps on board, the Arduino MEGA microcontroller was selected as an easy prototyping platform for operations. The Arduino MEGA is an open-source microcontroller board based on the ATmega1280. The Arduino MEGA features 54 digital I/O pins of which 15 provide pulse-width modulation (PWM) capability, and 16 analog pins. This allowed for the easy integration of various digital and analog electronic components and the ability to write custom source code with the support of the open-source community. The Arduino has been cheaply and successfully integrated into other oceanographic instrument prototypes in the past, including a low-cost fluorometer to study phytoplankton fluorescence [16]. The Arduino programming language, which is similar to C++, was used for programming the various MantaRay software modules, and Arduino IDE software was used to compile and download all software to the Arduino board.

Fig. 4 shows the general software block diagram that is used during a deployment to successfully process many samples of a given volume at a distinct sample interval. This software process replicates the sampling method described in Section III. The deployment software is written to conserve power and run very few processes at a time, helping the Arduino processor run efficiently. All processes on board are run in a linear fashion throughout the mission with the exception of a temperature and humidity interrupt function that actively monitors conditions in the pressure housing to alert the instrument if there is a leak or battery short circuit.

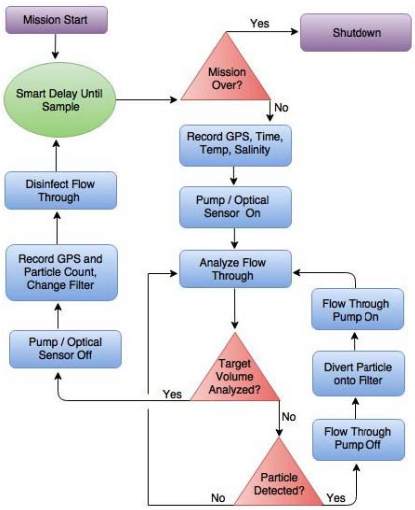

Fig. 4. MantaRay Deployment Software Block Diagram

V. Sensor Performance

MantaRay performance was determined at the bench by passing precut polyethylene particles of varying sizes through the instrument and monitoring the system for particle detection. Particles of 5, 4, 3, 2, 0.7, 0.5, and 0.3 mm were analyzed while circulating filtered seawater through the instrument. For each particle size, 20 particles were individually run through the instrument by placing them in front of the intake. This process was replicated 8 times for each particle size for a total of 120 data points used to compute the mean detection rate. Fig. 5 shows the performance curve of the MantaRay detection capability with decreasing particle size. Since the optical sensor operates on a trip sensor design, it is much more responsive to larger particles that block more of the laser path as they move through the flow stream. For this reason, detection rate decreases with particle size.

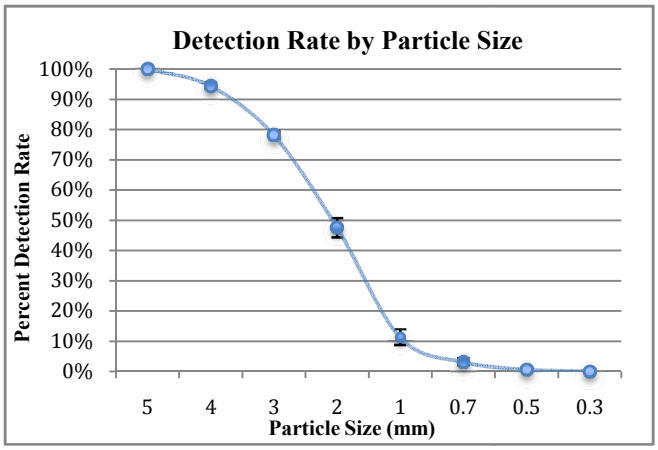

Fig. 5. MantaRay Particle Detection Rate (%) as a function of Particle Size (mm). Bars signify standard errors.

VI. Future Design Considerations

There are several design improvements that will be incorporated into the next generation MantaRay, making the instrument more efficient and able to gather additional data. The first and most important major design improvement will be the addition of an UV wavelength optical sensor that could differentiate various polymer types from opaque organic matter. Plastic polymers fluoresce in both the UV and near-IR wavelengths with distinct excitation and emission curves. Currently, the MantaRay prototype recognizes any opaque particle and archives it on a sample filter, so each filter will require further analysis once the instrument is retrieved. Adding a selective optical sensor will allow the MantaRay to parse out different particles in the flow-through and make intelligent decisions about what to archive versus what to exhaust. The feature will also give the instrument capability for real-time data acquisition, with the ability to actively communicate both concentration and polymer type in a given area. Another improvement to the optical sensor will be a beam splitter that can take the UV light source and spread the light out over the entire flow-through chamber. Currently, the two optical lasers cast a 2mm diameter beam across the center of the flow-through chamber, allowing particles to potentially flow around the beam and thus be missed. Another design improvement will be the miniaturization of the MantaRay so that it can be incorporated onto mobile platforms, like Autonomous Underwater Vehicles (AUVs), or remote controlled and Autonomous Surface Vehicles (ASVs). The current prototype was built for functionality and proof-of-concept, so a smaller and more efficient design will make the MantaRay more functional on multiple oceanographic platforms.

VII. Conclusion

It is clear that low-cost systems need to be put in place to monitor the ecosystem and human health risks of microplastics in our environment. The amount of funding that it takes to get out to the deep sea in research vessels is cost prohibitive for actively monitoring marine microplastic concentrations around the world at this time. A fleet of low-cost sensors like the MantaRay could increase our monitoring efforts and uncover some of the mysteries about marine plastics and how they disperse and degrade in the ocean. With plastic production rates growing exponentially, marine microplastic pollution is not going away any time soon. New technologies are needed to increase our awareness of this issue and to gather data that is economically prohibiting and difficult to collect with current research techniques. Additional refinement is needed on the current MantaRay prototype that will allow for selective processing of microplastics in a smaller package design. A field deployment for the current MantaRay prototype is set for Fall 2015.

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REFERENCES

[1] R. C. Thompson, "Lost at sea: where is all the plastic?," Science, vol 304, p. 838, 2004.

[2] K. L. Law, S. Moret-Ferguson, N. A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, and C. M. Reddy, "Plastic accumulation in the North Atlantic Subtropical Gyre," Science, vol. 329, pp. 1185-1188, 2010.

[3] L. S. Fendall, and M. A. Sewell, "Contributing to marine pollution by washing your face: microplastics in facial cleansers," Mar. Poll. Bull., vol. 58, pp. 1225-1228, 2009.

[4] M. A. Browne, P. Crumpf, S. J. Niven, E. Tueten, A. Tonkin, T. Galloway, and R. Thompson, "Accumulation of microplastic on shorelines worldwide: sources and sinks," Env. Sci. Tech., vol. 45, pp. 9175-9179, 2011.

[5] L. C. Woodall, A. Sanchez-Vidal, M. Canals, G. L. J. Paterson, R. Coppock, V. Sleight, A. Calafat, A. D. Rogers, B. E. Narayanaswamy, and R. C. Thompson, "The deep sea is a major sink for microplastic debris," Roy. Soc. Open Sci., vol. 1, pp. 1-8, 2014.

[6] C. J. Moore, S. L. Moore, M. K. Leecaster, and S. B. Weisberg, "A comparison of plastic and plankton in the North Pacific Central Gyre," Mar. Poll. Bull., vol. 42, pp. 1297-1300, 2001.

[7] L. A. Fernandez, W. Lao, K A. Maruya, C. White, and R. M. Burgess, "Passive sampling to measure baseline dissolved Persistent Organic Pollutant concentrations in the water column of the Palos Verdes Shelf Superfund site," Env. Sci. Tech., vol 46, pp. 11937-11947, 2012.

[8] E. L. Teuten, J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Bjorn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. H. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, and H. Takada, "Transport and release of chemicals from plastics to the environment and to wildlife," Phil. Trans. Roy. Soc. B: Biol. Sci., vol. 364, pp. 2027-2045, 2009.

[9] C. M. Rochman, E. Hoh, T. Kurobe, and S. J. the, "Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress," Sci. Repts., vol 3, pp. 1-7, 2013.

[10] M. A. Browne, S. J. Niven, T. S. Galloway, S. J. Rowland, and R. C. Thompson, "Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity," Curr. Biol., vol 23, pp. 2388-2392, 2013.

[11] M. A. Browne, A. Dissanayake, T. S. Galloway, D. M. Lowe, and R. C. Thompson, "Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.)," Env. Sci. Tech., vol 42, pp. 5026-5031, 2008.

[12] N. M. Hall, K. L. E. Berry, L. Rintoul, and M. L. Hoogenboom, "Microplastic ingestion by scleractinian corals," Mar. Biol., vol. 162, pp. 725-732, 2014.

[13] E. R. Zettler, T. Mincer, and L. Amaral-Zettler, "Life in the plastisphere: microbial communities on platic marine debris," Env. Sci. Tech., vol. 47, pp. 7137-7146, 2013.

[14] J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M Perryman, A. Andrady, R. Narayan, and K. L Law, "Plastic waste inputs from land into the ocean," Science, vol. 347, pp. 768-771, 2015.

[15] V. Hidalgo-Ruz, L. Gutow, R. C. Thompson, and M. Thiel, "Microplastics in the marine environment: a review of the methods used for identification and quantification," Env. Sci. Tech., vol 46, pp. 3060-3075, 2012.

[16] T. Leeuw,, E. Boss, and D. Wright, "In situ measurements of phytoplankton fluorescence using low cost electronics," Sensors, vol. 13, pp. 7872-7883, 2013.