

# Using infrared spectroscopy analysis of plastic debris to introduce concepts of interaction of electromagnetic radiation with matter

R M Anjos<sup>1</sup>, S S G Amaral, M C Muniz, R P Cardoso, T A S Bernardo, A Guerrieri and L L Lage

Laboratório de Radioecologia e Alterações Ambientais (LARA), Instituto de Física, Universidade Federal Fluminense, Av. Gal Milton Tavares de Souza, s/n, Gragoatá, 24210-346, Niterói, RJ, Brazil



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E-mail: [meigikos@mail.if.uff.br](mailto:meigikos@mail.if.uff.br)

## 1. Introduction

Many students have seen photos of a small turtle with a deformed shell that grew wrapped in a plastic six-pack ring or a sea turtle found by scientists with a plastic drinking straw up its nose [1, 2]. However, harmful plastic debris found on beaches and in the oceans are not limited to drinking straws or bags. There are several synthetic organic polymers that can be used to make different kinds of plastic materials and have resulted in billions of tons of waste that can reach the aquatic biome and are harmful to freshwater and marine communities as well as humans [3, 4]. Small pieces, known as microplastics, are very small (<5 mm) and can readily be ingested by marine organisms, causing dangerous threats to the food supply chain. Although plastic debris appears as particles of varying size, shape, color, and chemical composition, its origin or source cannot easily be identified by the naked eye. Sometimes, it is also difficult to identify whether debris is made of plastics materials. However, plastic debris sources can be revealed by applying basic concepts of the interaction of infrared radiation with matter [5]. If a sample is irradiated with infrared light,

a part of the radiation can be absorbed and provide detailed information about the structure of chemical compounds, such as the arrangement of nuclei and chemical bonds within the molecule. Chemical features of a molecule allow identification of the type of polymer that makes up a plastic material [3, 5].

Polymer identification of small-sized plastic debris can be performed by using infrared spectrometers. Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectrometers are usually found at universities in material characterization laboratories and can be used in teaching practices. On the other hand, if it is not possible to have an ATR-FTIR, mainly due to their cost-effectiveness and difficulty in handling, simpler systems, such as one-dimensional optical transmittance sensors, can be used for didactic purposes. This equipment can also be used in high schools. The basic Physics concepts needed to understand infrared spectrometry, such as energy conservation, optics, oscillations and waves, and principles of quantum mechanics are usually presented to students in the second-year of undergraduate courses in physics, chemistry and environmental engineering. Similarly, junior students in high school and first-year students

<sup>1</sup> Author to whom any correspondence should be addressed.

at undergraduate courses should also be able to carry out the experiments with one-dimensional optical transmittance sensors because no complex mathematical equations are used. Therefore, once these basic concepts or prerequisites are acquired, students can apply concepts of the interaction of infrared radiation with matter to unravel the impacts of plastic materials discarded in coastal and marine environments.

In this paper we describe a multidisciplinary approach to teaching the interaction of infrared light and the vibrating process of molecules to characterize plastic pollutants. The practical classes involve both indoor and outdoor activities, divided into four steps: choice of case study site; plastic debris sampling; sample preparation and physical and chemical characterization of plastic debris (size, color, shape and polymer type); data interpretation and identification of the main plastic debris sources. The first three steps, which include outdoor activities, can also be performed by students of all ages, as well as by geography, environmental science and biology teachers who are fundamental in multidisciplinary studies. The data interpretation step that involves the polymer identification is performed at the laboratory, by using ATR-FTIR and/or optical transmittance sensor systems. Finally, the identification of the main plastic debris sources and the final conclusions are tasks that can be performed in a multidisciplinary way.

## 2. Meso and microplastics

Since plastics are made from synthetic or semi-synthetic organic polymers (table 1), there are myriad sources of plastic material, such as industrial and agricultural waste, particulates from car tire wear, dust, landfill, wastewater, and deliberate littering [3, 6, 7]. In addition to its own toxic effects on the environment and public health, synthetic polymers can be rapidly colonized by microorganisms and act as vectors for the dispersal of harmful or even human pathogenic species. Therefore, plastic material can release toxic additives or concentrate additional toxic chemicals in the environment, such as bacteria or microbial communities, persistent organic pollutants (POPs), carcinogens, endocrine disrupting chemicals (EDCs), heavy metals [4, 6, 7]. Consequently, plastic debris and their toxic

additives are bioavailable for direct (inhalation/ingestion/skin contact) or indirect (food chain) human exposure [4, 7].

Currently, plastic debris are considered the most abundant and persistent marine litter in populated coastal and marine ecosystems. Once in the environment, plastic materials tend to become brittle and break into small pieces. Fragmentation can be accelerated when the plastic material is exposed to UV radiation under direct sunlight and/or physical abrasion in the sands and rocks of the beaches. However, due to their corrosion-resistant properties, most plastic debris resulting are hard-to-degrade materials and persist in the coastal and marine environments for a few centuries. As a consequence, they become floating debris widely dispersed by the wind and wave actions and therefore can be found in large areas of the sea surface [3]. Scientific works reveal that plastics can also be found deep in the sea, in the Antarctic Peninsula, among other remote habitats [5].

According to [3], plastic debris are colored particles (transparent, crystalline, opaque, white, red, orange, blue, black, grey, brown, green, pink, tan, yellow) classified according to their size range: macroplastics (>25 mm), mesoplastics (5–25 mm) and microplastic (<5 mm). Microplastics can be classified as primary or secondary depending on their actual source. Primary microplastics are originated directly from industrial activities can be found in household items, such as personal hygiene products (facial cleansers, toothpaste, exfoliating creams). In addition, virgin resin microbeads are widely used during plastics manufacture, usually presenting a pellet shape (cylinders, disks, spherules, flat, ovoid). Secondary microplastics are generated from the fragmentation of larger plastic debris due to the action of external agents (UV radiation, physical abrasion, etc). They usually have the shape of filaments, fragments, fibers, sheets, irregular films, broken edges, and granules. Recently, microplastics have been receiving attention due to their threat to environmental quality preservation. Besides the negative economic impacts on tourism, they can be ingested by numerous marine organisms, from plankton to crustaceans, fish, seabirds, turtles and marine mammals. Direct negative effects include stress, false satiety, obstruction of the intestinal tract, internal injury, inhibition of gastric enzyme secretion, reduced feeding stimuli, decreased

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**Table 1.** Types of plastic and their main applications. Modified from [3, 7].

Polymer	Application
Low-density polyethylene (LDPE)	Packaging, general purpose containers, shower curtains, floor tiles
High-density polyethylene (HDPE)	Milk containers, detergent bottles, tubing
Polyethylene (PE)	Supermarket bags, plastic bottles
Polyurethanes (PURs)	Elastomers, coatings, fibers, paints and varnishes
Polystyrene (PS)	Packaging foam, disposable cups, food containers, building materials
Polyvinyl chloride (PVC)	Pipes, window frames, flooring, shower curtains
Polypropylene (PP)	Packaging, bottle caps, ropes, carpets, laboratory equipment, drinking straws
Polyamides (PA) (nylons)	Textiles, toothbrush bristles, fishing lines, automotive
Polyethylene terephthalate (PET)	Soft drink bottles, food packaging, thermal insulation, blister packs
High impact polystyrene (HIPS)	Electronics, cups in vending machines, refrigerator liners
Acrylonitrile butadiene styrene (ABS)	Musical instruments, printers, computer monitors, drainage pipes, protective equipment
Polycarbonate (PC)	CDs, DVDs, construction materials, electronics, lenses
Polyester (PES)	Textiles

steroid hormone levels, delays in ovulation, failure to reproduce and starvation. Toxic effects include the development of reproductive abnormalities and cancer. To make matters worse, microplastics and plastic-associated contaminants can also be transported from prey to predator, reaching various trophic levels, including humans [4, 7].

### 3. Infrared spectroscopy

Infrared spectroscopy is widely used by physicists and chemists to gather information about the structure of a compound and as an analytical tool to assess the purity of a compound. The basic idea of this technique is that molecules of a substance are in continuous motion, i.e. they are not static but vibrating systems, which are in translation and rotation. Each atom in a molecule assumes a new position with time [3]. The total molecule energy ( $E_{\text{mol}}$ ) can be described in terms of vibrational processes  $E_{\text{vib}}$ , electron excitation  $E_{\text{el}}$ , and rotational energy  $E_{\text{rot}}$ :

$$E_{\text{mol}} = E_{\text{vib}} + E_{\text{el}} + E_{\text{rot}}. \quad (1)$$

A molecule is therefore full of oscillators of different dimensions. Their atoms can be excited to a higher level using electromagnetic radiation of appropriate energy/frequency. Vibration in a molecule containing two atoms, for example, is equivalent to a simple oscillator. In a classical description, a molecular vibration should behave like a mechanical vibration of two masses connected by a spring [3, 8]. Based on Hooke's Law,

the frequencies  $\nu$  of an oscillator that consists of two atoms of masses  $m_1$  and  $m_2$  are derived from a force constant  $f$  and the reduced mass  $\mu$ :

$$\nu = \frac{1}{2\pi} \sqrt{\frac{f}{\mu}} \quad \mu = \frac{m_1 m_2}{m_1 + m_2}. \quad (2)$$

The energy needed to excite most of the vibrational modes in organic molecules falls in the infrared spectral frequency region. To describe the spectra of molecules in the IR region, the vibration frequencies  $\nu$  are expressed by wavenumbers  $\bar{\nu}(\text{cm}^{-1})$  or wavelengths  $\lambda$  ( $\mu\text{m}$ ):

$$\bar{\nu} = \frac{\nu}{c} = \frac{1}{\lambda}. \quad (3)$$

When a molecule is irradiated by infrared light ( $4000\text{--}250\text{ cm}^{-1}$  or  $2.5\text{--}40.0\ \mu\text{m}$ ), it absorbs the radiation under some specific conditions. When the radiant energy matches the energy of a specific molecular vibration, absorption occurs. Following a quantum mechanical description, the energy levels of the oscillator can be characterized by the quantum number  $n$  one-dimensional:

$$E_{\text{vib}} = h \left( n + \frac{1}{2} \right) \nu \quad n = 0, 1, 2, \dots \quad (4)$$

being  $\nu$  the frequency of the radiation that is absorbed by the molecule and Planck's constant  $h = 6.62 \times 10^{-34}\text{ J}\cdot\text{s}$ . From equations (2)–(4), one can observe that the combination of atoms leads to distinguishable absorption spectra of different molecules. Each molecule that interacts with infrared light can assume only discrete

energy levels and the number of these energy levels per molecule is not limited to one but contains several discrete states [3]. The lowest energy state is defined as ground state, and higher energy states are defined as excited states.

However, the absorption and emission of real molecules are more complicated. Other effects must be considered, e.g. the oscillators of real molecules are anharmonic [3]. Then,  $E_{\text{vib}}$  can be obtained from a quantum mechanical anharmonic oscillator:

$$E_{\text{vib}} = h\nu \left( n + \frac{1}{2} \right) - \chi h\nu \left( n + \frac{1}{2} \right)^2 \quad (5)$$

where the first part of equation (5) represents a harmonic term while the second part represents an anharmonic term of vibrational constant  $\chi$ . The energy of the absorbed infrared light is equal to the energy difference ( $\Delta E$ ) between a certain energy level of vibration (excited) and another energy level of vibration (ground state) of the molecule:

$$\Delta E = h\nu = E_{\text{excited}} - E_{\text{ground state}}. \quad (6)$$

In general, vibrational modes in infrared spectroscopy can be divided into two different groups: stretching (the molecule stretches and contracts) and bending (change of the bonding angle). The main polymers used to manufacture plastic materials are mainly composed of carbon, hydrogen, oxygen, and nitrogen. Inside of these polymers there are typical vibrational groups of the carbon backbone like CH, CH<sub>2</sub>, CH<sub>3</sub>, CO, CN etc. For the stretching group, there is symmetric and asymmetric stretching. For bending, there is twisting, rocking, wagging and scissoring. Each of them performs characteristic vibrational modes with specific frequencies [3]. Figure 1 illustrates twelve different vibrational modes of a  $-(\text{CH}_2)-$  group within polyethylene.

The energy of a molecular vibrational state can be estimated by equation (5). Taking a CH-stretching vibration of a common polymer as an example, the wavenumber for a transition from the ground state to the first excited state is [3]:

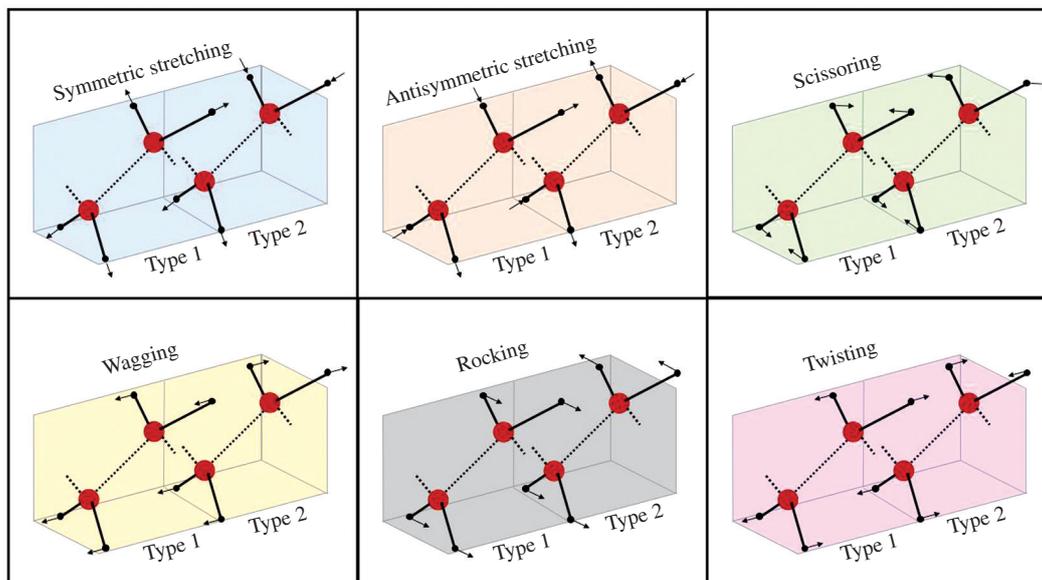
$$\begin{aligned} \frac{\Delta E_{\text{vib}}(0 \rightarrow 1)}{h.c} &= \left( \frac{\bar{\nu} \cdot 3}{2} - \frac{\chi \bar{\nu} \cdot 9}{4} \right) - \left( \frac{\bar{\nu}}{2} - \frac{\chi \cdot \bar{\nu}}{4} \right) \\ &= 4179 \text{ cm}^{-1} - 1441 \text{ cm}^{-1} = 2738 \text{ cm}^{-1}. \end{aligned} \quad (7)$$

According to equation (7), infrared radiation with a wavenumber of  $2738 \text{ cm}^{-1}$  (corresponding

to a wavelength  $\lambda = 3.65 \mu\text{m}$ , see equation (3)) will be absorbed by the molecule to perform the transition of the described CH-stretching vibration. In addition to the  $\nu 0 \rightarrow \nu 1$  transition, it is possible to reach a state of a higher energy level, e.g.  $\nu 0 \rightarrow \nu 2$  etc, by absorption of the corresponding higher energy (e.g.  $5882 \text{ cm}^{-1}$  or  $1.70 \mu\text{m}$  for the CH-stretching vibration). This phenomenon is called overtone vibration and it is the process of interest in the near-Infrared spectroscopy.

Considering that the frequency  $\nu$  depends on the chemical properties of the vibrational group, chemical compounds can be differentiated according to their vibrational frequencies [3, 5]. The infrared spectrum can be divided into three regions of frequency or wavelength: the near (up to  $2.5 \mu\text{m}$ ), mid (from  $2.5$  to  $25.0 \mu\text{m}$ ), and far infrared (from  $25$  to  $300 \mu\text{m}$ ). Within the mid-infrared (MIR) spectrum (figure 2), the fundamental stretching modes of CH that arise near the  $3.45 \mu\text{m}$  are found. The symmetric and asymmetric modes of polyethylene, for instance, lie at  $3.41 \mu\text{m}$  and  $3.51 \mu\text{m}$ , respectively. The modes of CH groups neighboring C=C bonds are found at the higher wavelength of  $3.23 \mu\text{m}$ . The wagging bands lie between  $8.48 \mu\text{m}$  and  $7.41 \mu\text{m}$ . In chains containing CH<sub>2</sub> the twisting bands appear in the same wavelength region. The rocking vibrations cause a characteristic band for long chains at  $13.89 \mu\text{m}$ .

Infrared spectroscopy has an advantage over the other spectroscopy techniques because it hardly requires any sample preparation. Besides, microplastics of all kinds can be analyzed with high accuracy within short measurement times. The mid-infrared region (MIR) is of greatest practical use to the organic chemistry, including therefore the plastic debris analysis [3, 4]. Although less used, spectra from plastic debris can also be generated with good quality and high intensity in the near-infrared (NIR) region, where the vibrational bands are mainly generated by the overtones of stretching vibrations of groups containing hydrogen and combinations of these stretching vibrations with wagging and/or rocking vibrations [8]. The first overtone of the CH stretching mode appears near  $1.70 \mu\text{m}$  and the second near  $1.20 \mu\text{m}$  (figure 3). Comparable to the fundamental vibration, the overtones are also observed at shorter wavelengths if the CH functional group is about groups such as C=C or in



**Figure 1.** Schematic overview of 12 different vibrational modes of a  $-(\text{CH}_2)-$  group within polyethylene without C–C vibrations. Carbon atoms are illustrated as red and hydrogen atoms as black circles, while the vibrational vectors are given by arrows. Each of the six vibrational modes can be subdivided into two types according to in-phase or counter-phase vibrations. Modified from [3].

an aromatic C–C bond. Combination bands lie between the fundamental vibrations and the various overtones (e.g. 2.30 and 1.40  $\mu\text{m}$ ). The first overtone of NH is located near 1.50  $\mu\text{m}$  and the second near 1.10  $\mu\text{m}$ . An interesting tendency observed in NIR spectra is that all plastic materials show absorption peaks around 1.70  $\mu\text{m}$ , which is attributed to a stretching vibration of the C–H bond [8, 9].

#### 4. 1D optical transmittance sensor

A disadvantage of applying the MIR/NIR spectrometers in physics education is that these systems are not always available in high schools because of their cost-effectiveness and handling. However, a substitutive system can be used to experimentally approach concepts on the interaction of infrared radiation with matter: a low-cost optical transmittance sensor. Although low-cost alternative systems will not have the high sensitivity that MIR/NIR spectrometers do, they can be successfully used for didactic purposes. These systems use laser diodes (LD) or infrared LEDs as sources of monochromatic infrared light (only one-wavelength radiation). According to [10], the plastics from household wastes (such as PE,

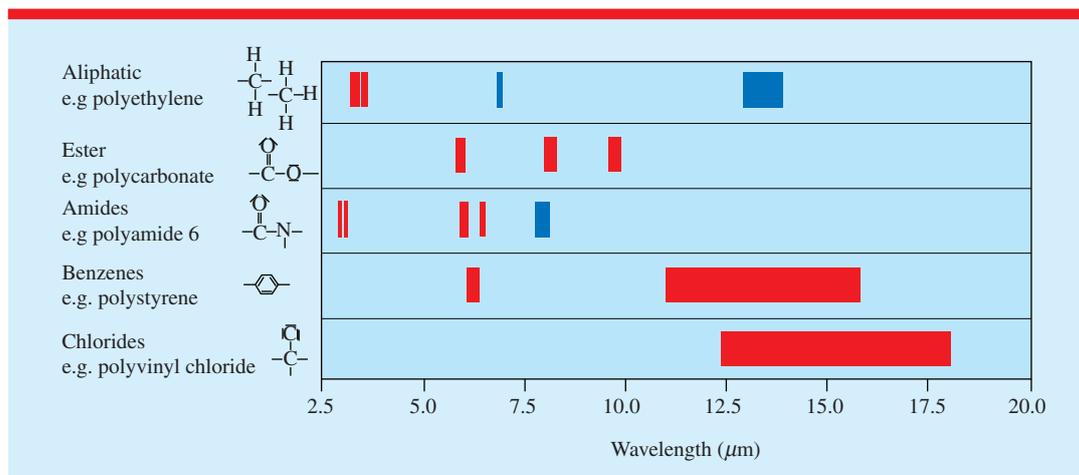
PP, PVC, PS and PET) can be reliably identified by the first overtone of the C–H bands (near to 1.7  $\mu\text{m}$ ), technical non-black plastics around 1.0  $\mu\text{m}$ , and black plastics only in the MIR region.

A one-dimensional optical sensor system was mounted according to figure 4. In this system, an infrared beam  $I_o$  from the LD/LED that passes through a plastic sample is detected by a photodiode. According to the Beer–Lambert–Bouguer law, an infrared radiation of intensity  $I$  that penetrates a material of thickness  $\Delta x$  is diminished by  $\Delta I$  due to the vibrations with absorptivity  $\alpha$  of component concentration  $c^*$  following the simple relationships:

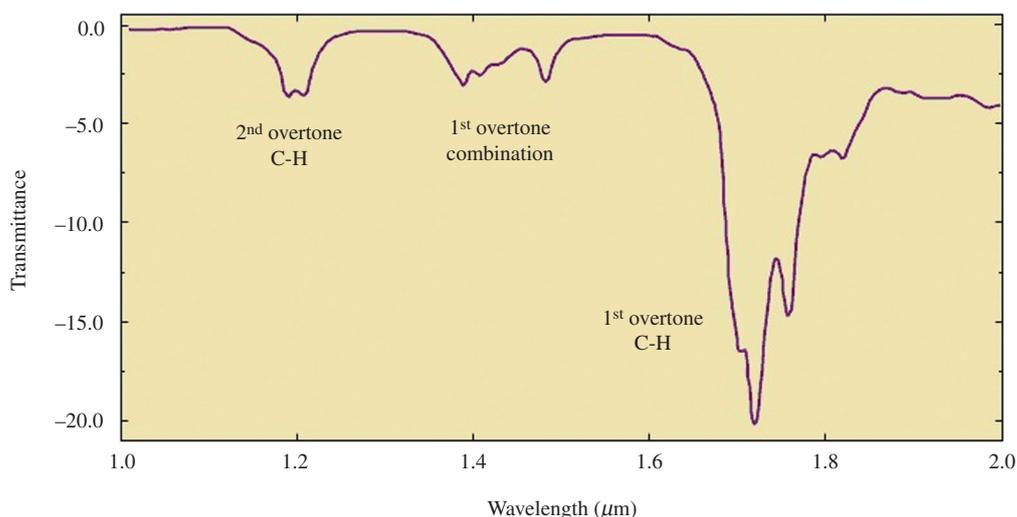
$$\Delta I = -\alpha c^* I \Delta x \quad (8)$$

$$T = \frac{I}{I_o} = e^{-\alpha c^* d}. \quad (9)$$

The transmittance  $T$  describes the response of the material with a thickness  $d$  related to the initial radiation intensity  $I_o$ . Therefore,  $T$  depends on parameters such as the thickness, density, color and polymer type of the analyzed sample, as well as on the infrared beam wavelength. When  $I$  is compared to the incident light intensity  $I_o$  (without sample), the ratio can be defined as *transmittance*



**Figure 2.** The most important vibrational groups for microplastics analysis. Red bars describe positions of stretching vibrations, while blue bars describe bending vibrations. Modified from [3].



**Figure 3.** Transmission in PE foil in the MIR/NIR spectral region, showing overtones and combination bands in the NIR spectrum. Modified from [9].

percentage  $T$  (%), which means that  $T$  is multiplied by 100. Forming the logarithm of  $T$ , the absorbance  $\alpha c * d$  is obtained, which is linear in concentration and sample thickness:

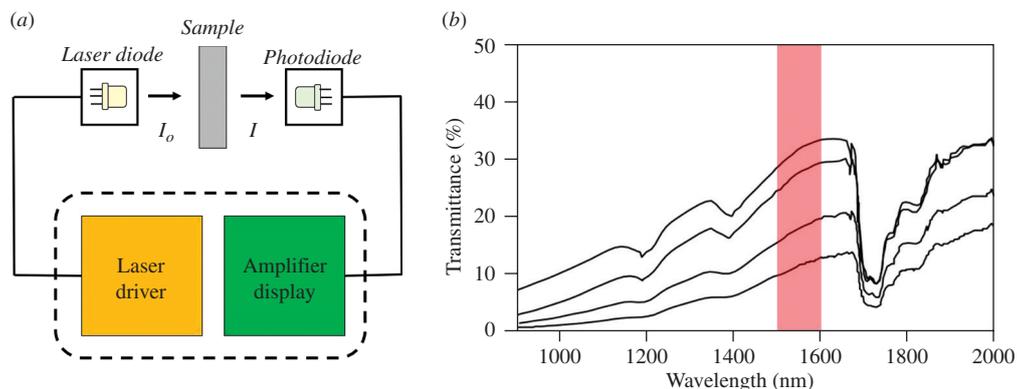
$$\alpha c * d = \ln I - \ln I_0. \quad (10)$$

### 5. Indoor and outdoor activities

The practical activities were performed and tested for the first time during the classes of Modern Physics Laboratory II (first semester 2019) of the Federal Fluminense University. In this course, 12

physics undergraduate students and three physics teachers from public high schools were enrolled. The four students who obtained the best final evaluations were invited to develop didactic materials for this activity and to be coauthors of this work. These indoor and outdoor activities were subsequently successfully applied to 15 physics undergraduate students enrolled in the same course. In both cases, the outdoor activities (fieldwork) were carried out in the Jurujuba harbor (22° 55' 52" S, 43° 06' 59" W), a touristic area of the Niterói municipality (Rio de Janeiro State, Brazil) and

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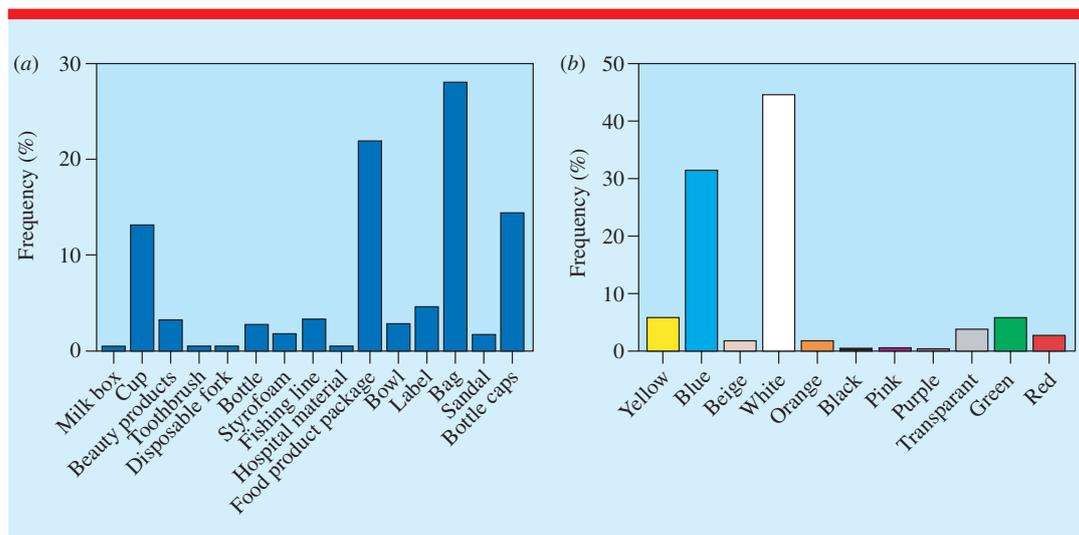
**Figure 4.** (A) Illustration of the optical transmittance sensor and (B) wavelength region used for transmittance measurements in plastic debris. Modified from [10].

near the University. Jurujuba was chosen because it is located at the entrance of the Guanabara Bay and shows a concave shape that facilitates the debris accumulation during undertow periods, besides being a fishing boat mooring. Therefore, it is an ideal location to study marine debris depositions on the beach. Figure 5 shows a bar chart of the typical plastic objects found by the students on the beach, which can be considered as the main plastic debris sources.

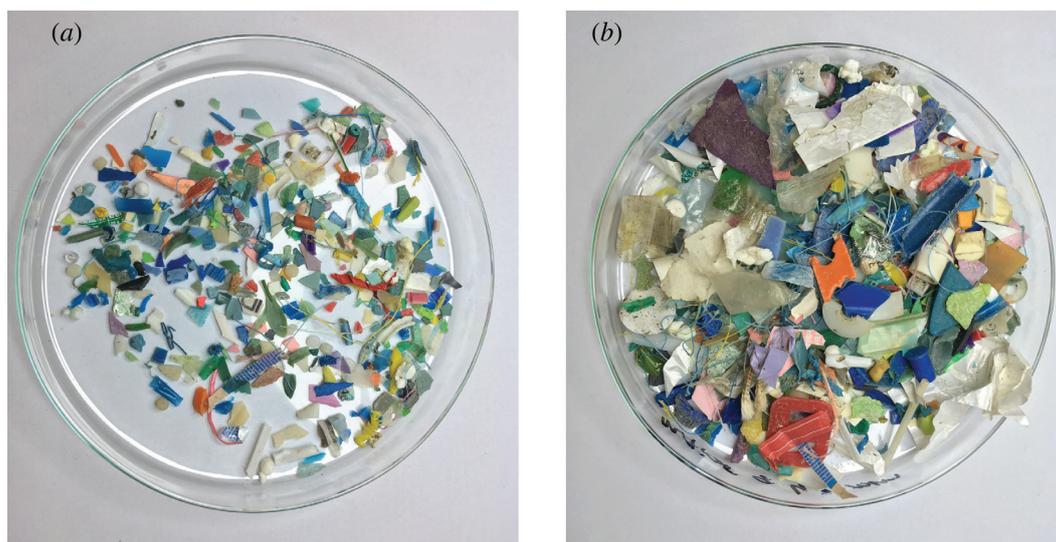
A 150 m horizontal transect, located on the high tide line, was established for the plastic material sampling. This line shows marine litter accumulation zones from the sea waves. About 20 sampling sites that did not show signs of being disturbed by recent human action were chosen. Plant fragments, gravel and shells were previously removed. Small plastic debris was randomly collected on the sand surface by using a metallic spatula. At the laboratory, the samples were dried in an oven at 60 °C for 24 h. This temperature allows debris to dry without material damages such as deformation, melting or burning. Subsequently, the samples were sieved with 5 mm and 1 mm mesh. The materials retained in the 1 mm mesh were transferred to a 500 ml beaker in order to separate the microplastics (size < 5 mm) from other compounds such as sand and organic materials. The most common separation method is the density flotation by using a hypersaline solution. Besides being an efficient separation method, unlike other chemicals saline solutions do not pose health risks to the students. Therefore, a hypersaline solution with a density of 1.2 g cm<sup>-3</sup>, previously filtered, was added to the beaker

containing the samples and it was stirred manually with a glass rod for 3 min. Then, it was left at rest for 10 min. A similar procedure was performed for debris ranging from 5 to 25 mm (mesoplastics). Subsequently, the supernatant materials in the respective beakers were collected and filtered to extract the microplastics (figure 6(a)) and mesoplastics (figure 6(b)). At the end of this procedure, 719 mesoplastics and 434 microplastics were identified, separated and dried again in an oven at 60 °C for 24 h. Their color and shape were initially identified in a stereoscope and arranged in bar charts (figures 7 and 8, respectively). Both secondary (fragments and filaments) and primary (cylinder, spherule and flat pellets) plastic debris of several colors were observed.

The chemical characterization of the debris was initially performed applying ATR-FTIR spectroscopy, using an ATR detector in a Tensor II Fourier Transform Spectrometer (Bruker Optik GmbH). Tensor II is an equipment that operates in the mid-infrared (MIR) range and has high sensitivity in discriminating various types of materials [11]. Therefore, it can confirm whether the visually identified sample was really a plastic material, whether it contains other aggregate materials, and the chemical composition of the plastic debris (polymer class). The characterization of the plastic debris was performed from absorbance  $x$  wavelength spectra by comparing the absorption bands (AB) of the samples with those in the published literature [12]. The three main polymer types observed were (figure 9): Polyethylene (PE—AB: 3.431, 3.515, 6.840, 13.70, 13.95  $\mu\text{m}$ ), Polypropylene (PP—AB: 3.390, 3.431, 3.524,



**Figure 5.** Main plastic objects found on the Jurujuba Beach, sorted by (A) application and (B) color.



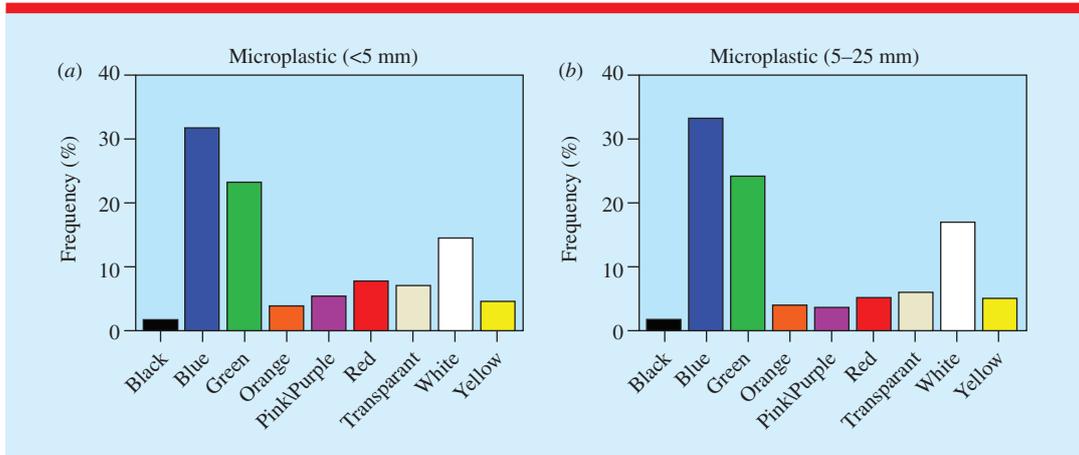
**Figure 6.** Plastic debris sampling with sizes (A) <5 mm (microplastics) and (B) 5–25 mm (mesoplastics).

6.873, 7.262, 8.576, 10.03, 10.29, 11.91, 12.38  $\mu\text{m}$ ), and Polystyrene (PS—AB: 3.307, 3.512, 6.246, 6.702, 6.892, 9.737, 14.41, 18.62  $\mu\text{m}$ ).

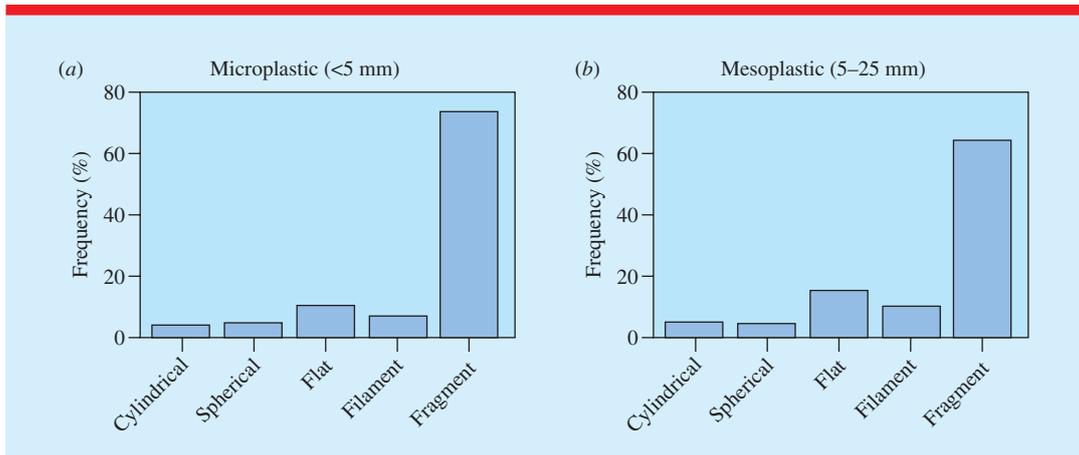
According to table 1 and [3, 4, 12], PE is typically used to make supermarket bags, plastic bottles and fishing net, generating secondary microplastics (filaments/fibers, irregular, broken edges, and granules). PE is also used in the manufacture of microbeads or pellets (cylinders, disks, spherules, flat, ovoid). PP is typically used

to make packaging, bottle caps, ropes, carpets, laboratory equipment, drinking straws, folders, food packaging, hinged caps and car bumper, generating similar secondary microplastics. PS is typically used to make packaging foam, disposable cups, food containers and building materials. Figure 10 shows that 98% of the micro and meso-plastic debris analyzed by the ATR-FTIR system were produced from PE and PP materials. This finding is consistent with Niterói's social and

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**Figure 7.** Plastic debris sampling on the Jurujuba Beach sorted by color, being (A) microplastics and (B) mesoplastics.

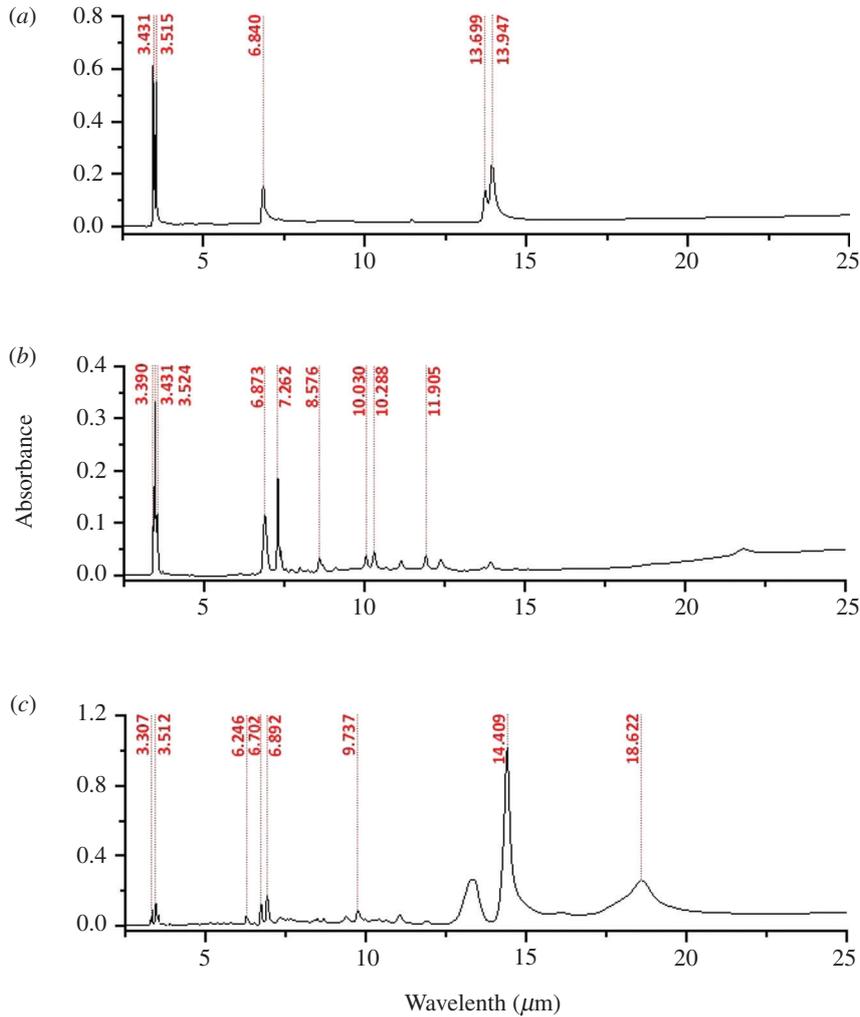


**Figure 8.** Plastic debris sampling on the Jurujuba Beach sorted by shape, being (A) microplastics and (B) mesoplastics.

industrial habits (figure 5): the sampled plastic debris comes mainly from household waste.

In order to test the effectiveness of a low-cost optical transmittance sensor that can be used in the classroom activities, we built a one-dimensional optical transmittance sensor system (figure 11(a)), following the technical information from the [8–10]. Its estimated cost is around US\$ 3000, while a MIRS system costs around US\$ 50000. Our system is based on the use of indium gallium arsenide (InGaAs) detectors, which operate within the near infrared range, emitting an infrared light with wavelength next to the first overtone of the C–H band (1.7  $\mu\text{m}$ ). As an infrared detector, it was used an InGaAs PIN

photodiode that covers a wide spectral response range from 0.9  $\mu\text{m}$  to 1.7  $\mu\text{m}$ , photosensitive area of 3 mm in diameter, and photosensitivity around  $1.1 \text{ A W}^{-1}$  at 25  $^{\circ}\text{C}$ . A laser diode that emits infrared light at a peak wavelength of 1.55  $\mu\text{m}$  (which allows it to operate between 1.5 and 1.6  $\mu\text{m}$ , see figure 4(b)), radiant flux of 1.9 mW at 25  $^{\circ}\text{C}$ , was used as a light source. An LED that emits infrared light at a peak wavelength of 1.55  $\mu\text{m}$  could also be used but, unfortunately, it was not available at the laboratory. To measure the plastic debris, samples with sizes  $> 5 \text{ mm}$  (mesoplastics) were selected. Microplastic samples ( $< 5 \text{ mm}$ ) did not show satisfactory results because of the geometrical configuration of our



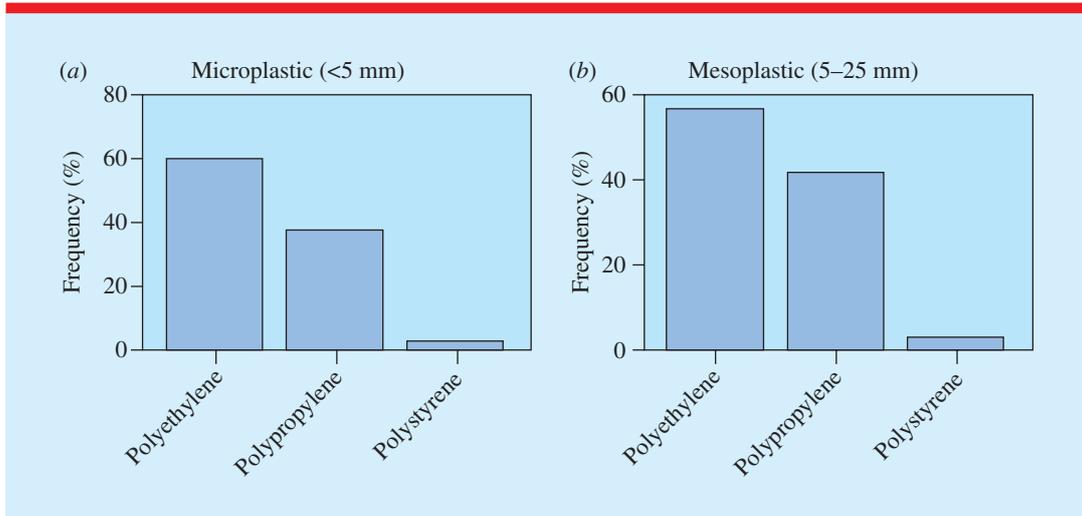
**Figure 9.** Typical MIRS spectra obtained for (A) polyethylene; (B) polypropylene; and (C) polystyrene.

system. Indeed, often the sample was smaller than the light beam diameter.

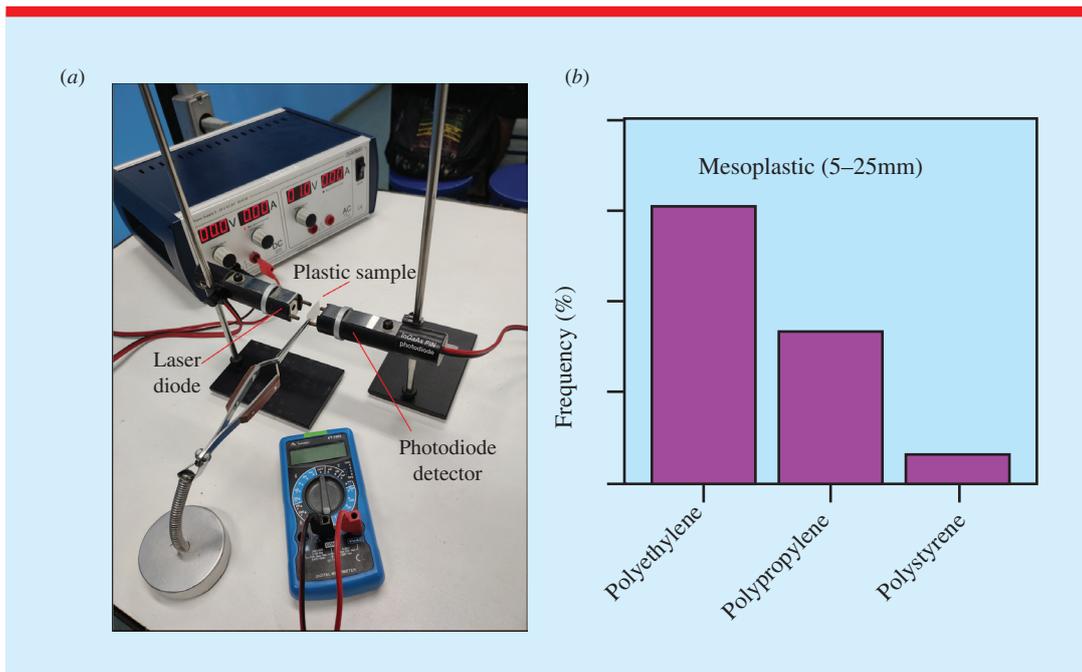
Since the transmittance  $T$  (equation (9)) depends on parameters such as thickness, density, color and polymer type of the analyzed sample, a few simple measurements may be proposed. However, it is important to remember that to study the effect of a given parameter, it is fundamental to keep the others fixed, since this device consists of a simple optical system. In order to assess the response of the transmittance to variations in sample thickness,  $2.5\text{ cm} \times 2.5\text{ cm}$  pieces from transparent PET bottles of different thicknesses  $d$  were selected. The result confirmed the expected behavior by equation (9), where the transmittance  $T$  decreases exponentially with

increasing thickness  $d$ . Tests about the transmittance response to sample color were performed by using transparent, blue and green polypropylene (PP) debris of 1.5 mm thickness. Mean transmittance values of  $95\% \pm 5\%$  (transparent),  $90\% \pm 5\%$  (blue) and  $65\% \pm 5\%$  (green) were obtained. The results are comparable with those observed in [10]. In order to evaluate the transmittance variation with polymer type, we have used 1.5 mm thick transparent plastic debris and mean values of  $95\% \pm 5\%$  (PP),  $85 \pm 7$  (PE), and  $66\% \pm 7\%$  (PS) were obtained. Given that the transmittance variation as a function of polymer type was obtained from samples in which the polymer was known, the obtained results could be used as reference values for future analysis.

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**Figure 10.** Main polymer types observed on the Jurujuba Beach by using the ATR-FTIR system, being (A) microplastics and (B) mesoplastics.



**Figure 11.** (A) Setup of the low-cost optical transmittance kit (the InGaAs detector and laser diode were installed inside old thermal radiation sensors modules available at the lab), and (B) the main types of mesoplastic polymer from the Jurujuba beach by using this kit.

Therefore, it was possible to experimentally characterize the set of mesoplastic samples from the Jurujuba beach by using our optical sensor. A bar chart for the distribution of the main mesoplastic polymers found in Jurujuba beach was obtained

by using the low-cost sensor (figure 11(b)). The results (94% of the mesoplastic debris were produced from PE and PP materials) are like those obtained from the ATR-FTIR system (figure 10). These findings indicate that a one-dimensional

optical transmittance sensor can be used as an auxiliary tool to teach concepts of the interaction of infrared radiation with matter, as well as to correlate them with relevant themes in the area of environmental science.

At the end of the Modern Physics Laboratory II classes, the 30 students who participated in these indoor and outdoor activities during 2019 noticed that, in addition to learning interesting topics of Modern Physics, they became aware of the importance to avoid the use of various plastic objects, which can be easily replaced by materials that do not harm the environment. They also understood the importance to expand the Brazilian plastic recycling services in order to mitigate the microplastic pollution in our coastal and marine environments. These results could be confirmed by finding a significant increase in the quality of the activity reports presented by the students. Since these reports are used as a continuous assessment of the students, they provided an increase of the final grades.

## 6. Conclusions

Through a theoretical and experimental activity about infrared radiation and its interaction with matter, undergraduate students had contact with an important theme: microplastic pollution effects in coastal and marine systems. By the end of the activity, the students understood important concerns about the degradation of coastal and marine environments, being able to visualize the science beyond the basic physics concepts traditionally taught within classrooms. A complete understanding of nature poses the challenge of crossing boundaries of two or more disciplines to understand complex problems in our society. In terms of teaching materials development, the three physics teachers from public schools who participated in this course are building low-cost optical transmittance sensor kits to be used in high school.

## Acknowledgments

The authors would like to thank CNPq (302112/2018-9), CNPQ/PIBIC, CAPES (88887.353731/2019-00), PIBITI/PIBINOVA, FAPERJ (E-26/202.794/2017), and IAEA (RLA7022) for their financial support.

## ORCID iDs

R M Anjos  <https://orcid.org/0000-0003-3314-8602>

SSG Amaral  <https://orcid.org/0000-0003-3690-7264>

M C Muniz  <https://orcid.org/0000-0003-0633-6755>

R P Cardoso  <https://orcid.org/0000-0002-0685-7764>

Received 29 September 2019, in final form 7 December 2019

Accepted for publication 17 December 2019

<https://doi.org/10.1088/1361-6552/ab630b>

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**R P Cardoso** is a physicist with a PhD in Applied Nuclear Physics who is developing his postdoctoral research at the LARA. He is currently applying nuclear techniques including stable isotopes to identify triggers of harmful algal blooms.



**R M Anjos** is a nuclear physicist and associate professor at the Physics Institute of the Universidade Federal Fluminense. He coordinates the Laboratory of Radioecology and Environmental Change (LARA) where multidisciplinary research activities are developed.



**T A S Bernardo** is an undergraduate physics student at the Universidade Federal Fluminense. She is also participating in a LARA's project related to improving water use associated with climate change adaptation and mitigation strategies in agriculture.



**S S G Amaral** is an undergraduate physics student at the Universidade Federal Fluminense. She is also developing a scientific research project at the LARA related to the environmental impacts of microplastic pollution on Brazilian coastal ecosystems.



**A Guerrieri** is an undergraduate physics student at the Universidade Federal Fluminense. She is also involved in studies related to gauge theory for gravitation, a process for building gravity theories inspired on quantum gauge field theories.



**M C Muniz** is a physicist with a PhD in Marine Biology who is developing his postdoctoral research at the LARA. His studies are related to ocean acidification, eutrophication, pollutants and their impacts on coastal marine ecosystems.



**L L Lage** is an undergraduate physics student at the Universidade Federal Fluminense. He is also involved in studies of carbon-based systems and now is looking for Moiré patterns in 2D-carbon allotrope lattices.