Optical transmission spectra study in visible and near-infrared spectral range for identification of rough transparent plastics in aquatic environments

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Estimate surface roughness of microplastics by transmittance & refractive index.
Differentiating rough from smooth microplastics by transmittance trends.
Ranking microplastics by transmittance.
Ranking microplastics by thickness.

Erosion of microplastics due to residence time in aquatic environments causes roughening of the microplastic. Unfortunately, currently used measurement methods do not provide information on the surface roughness of the microplastic embedded in water. In this study we propose a novel method by using transmittance to get information on the magnitude of the surface roughness of microplastics and to rank microplastics by thickness.

For such a purpose, we studied optical properties such as dispersion, absorption of both plastics and water in the partial spectral range of visible light (Vis), transmission and scattering of light by plastic sheets, as well as, the calculated sample thickness in the Vis region. These were explored for the detection of both smooth and roughened plastic sheets immersed in water. Moreover, by using the transmission spectrum and refractive index of both plastic and water it is possible to estimate the average surface roughness of plastic samples. Our results suggest that the optical properties in the Vis region offer an interesting way for the detection of both rough and smooth plastic sheets and for ranking the type of plastics in an aquatic environment.

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1. Introduction

Plastic products are common in our daily lives and are used in both households and industries for various purposes because of their unique properties i.e., lightweight, durability, versatility and
low cost of production (Hammer et al., 2012; Ivleva et al., 2017). Unfortunately, large and small plastic debris end up polluting water bodies, consequently, endangering the health of various species in an aquatic environment (Cole et al., 2011). Large plastics pollution is due to the intense human activities around the coastal areas (Zhou et al., 2018).

Primary nano- and micro size plastics are due to such original plastic products that are used, e.g., in cosmetics, toothpaste, etc. which, reaching water bodies, reduce the water quality and lead to loss of biodiversity (Thompson et al., 2009; Gall and Thompson, 2015). Because of their small size and low concentration in water, these plastics are rather difficult to detect.

Secondary nanoplastics (NPs) and microplastics (MPs) having rather a wide size distribution between 100 nm and 5 mm are the result of decomposition of large plastics by mechanical and chemical processes, together with emission of primary microplastics and nanoplastics. These contaminate water bodies through coastal areas, causing serious environmental and health concerns (Eriksen et al., 2014; Jambeck et al., 2015; Yokota et al., 2017). Moreover, due to their small size, MPs cause harm to organisms in an aquatic environment (Law and Thompson, 2014). A strongly emerging field of detoxification of heavy metals in water is based on photocatalyst (Wu et al., 2018), which is a powerful method in treatment of e.g., industrial wastewaters (Tahir et al., 2019). This type of cleaning of water might include detoxification of MPs in water but this has not been demonstrated yet. Thus, MP pollution is a global concern that calls for immediate attention (Plastics Europe, 2019).

To detect microplastics in water bodies is a challenging task. This is possibly due to several reasons, among them is photo-bleaching (when the colored plastic debris are subjected to ultra-violet (UV) radiation thus losing color, and consequently rendering such microplastics difficult to detect in the aquatic environment). Variation of density amongst different plastic particles is also another reason which hinders the MPs detection because the particles settle at different depths in water bodies: some float, others sink to the bottom whilst others settle at different depths. The final reason is the continuous drifting of plastic debris on the water surface, this may cause wear which leads not only to the reduction of plastic size but also roughening of the plastic surface and hence complicating the detection process. The surface roughness of MPs has a crucial role in the estimation of the aging of MP such as i.e. the study of MPs residence time in water (Iokaimidis et al., 2016). Moreover, surface roughness has a role in the adsorption of contaminants over MPs (Fei et al., 2019; Pan et al., 2019) because other particles and organisms (such as algae) are attached to the plastic particles through adsorption, causing organic growth which leads to a non-homogenous particle.

Methods which are visual, chemical and optical have been proposed for the detection of microplastics in sediments from water bodies (Hidalgo-Ruz 2012; Van Cauwenberghe, Vanreusel, Mees and Janssen, 2013; Harrison et al., 2012; Léger and Gerds, 2015; Thompson et al., 2004; Ng and Obbard, 2006; Vianello et al., 2013; Harrison et al., 2012). However, most of these methods are laborious, time-consuming, complex and the equipment is often expensive. Raman spectroscopy, for instance, is one of the promising methods for microplastic detection, in a recent work, it was applied to observe individual microplastic particles in tap water and was able to detect microplastics smaller than 0.1 mm (Knüggendorf et al., 2019). Recently, a hyperspectral imaging device was also applied from a simple and rapid detection of microplastics in seawater utilizing the near-infrared (NIR) spectral region (Shan et al., 2019). However, it involves chemometrics, i.e., principal component analysis (PCA) and support vector machine. However, our goal is to develop inexpensive optical sensors that are affordable and suitable for the in-situ detection of MP in natural water bodies.

This work advances the research initiated in (Peiponen et al., 2019) where it was shown that plastics embedded in water and having smooth surfaces can be identified by their transmission spectrum in NIR spectral region. However, due to tidal waves of oceans, waves of lakes and streams of rivers, and ocean currents such as those in the North Sea, plastic debris can be subjected to wear causing roughening to their originally smooth surfaces. Furthermore, the roughening of plastics can also happen in municipal wastewaters that are subject to cleaning in wastewater plants. Filtrated water or wastewater plant may contain roughened microplastics which constitute a substrate for bacterial and virus growth (Hosain et al., 2018; Wang et al., 2018). Moreover, drifting of MP in water either floating or sunken depends on surface roughness (Phal et al., 2019; Reisser et al., 2015). By monitoring the surface roughness of plastics in water, one can obtain the relevant information on their residence time (Iokaimidis et al., 2016). Although advanced detection methods such as FTIR and Raman spectroscopies are useful in the detection of plastic types, they do not provide information on the surface roughness. We, therefore, propose a novel method to rank different types of plastics and detect surface roughness of an MP using a simple optical measurement technique that can be adapted for field application.

Intending to develop portable devices for such measurements, we have demonstrated in our recent work, the prototype of a portable optical sensor which can detect both transparent and translucent microplastics in freshwater (Asamoah et al., 2019). The prototype measures simultaneously the specular laser light reflection and transmission of red laser light lasing at 635 nm, from microplastic particles immersed in water volume. The study of MPs carried out by Asamoah et al. does not identify the type of microplastic, but this is achievable by exploiting the Vis–NIR transmission spectrum (Peiponen et al., 2019).

The objective of this work is two-fold namely, to detect surface roughness and rank MPs. The MPs considered in this work assumes size closer to the maximum size of the definition of an MP, such as 1–5 mm, because it takes a long time of weathering in water and many steps of fragmentation for microplastics to reach size less than 1 mm (Julienne et al., 2019). Ranking of plastics is useful for the identification of MP types while the surface roughness is a measure of the aging of MP in water and has a crucial role in the adsorption of foreign material over MP. These are achieved based on the transmission spectra and light dispersion properties. In this paper, we consider the transmission spectra of both smooth and rough plastics in Vis–NIR spectral range but select the Vis spectral region for further analysis, because of the large difference of transmittance for rough and smooth samples. We deal briefly with theoretical concepts of the wavelength-dependent complex refractive index, the absorption coefficient of plastic with water as ambient medium (intrinsic absorption coefficient), and calculated sample thickness, to give at least a qualitative picture of the optical phenomena involved.

2. Theory

Light interaction with a macroscopic medium involves reflection, refraction, absorption, and transmission of light. The strength of these phenomena depends on the so-called wavelength-dependent complex refractive index of a medium, n + iκ, where n is the refractive index, k the extinction coefficient, and i is the imaginary unit. The extinction coefficients depend on the strength of light absorption in the medium. Hence, media can be identified by spectroscopic fingerprints that contribute to the behavior of the complex refractive index. The refractive index (RI) ratio is one of the
key parameters that has been used previously to characterize marine particles in water (Aas, 1996). To apply the RI ratio in this work, we replace the marine particles by plastics to obtain $n_{\text{plastic}}/n_{\text{water}}$, where $n_{\text{plastic}}$ is the refractive index of plastics (measured by ellipsometer) and $n_{\text{water}}$ is the refractive index of water extrapolated by Partington’s formula (Peiponen et al., 2001).

The concept of roughened plastics immersed in water is closely related to immersion liquid method utilized in various studies (Niskanen et al., 2010; Nussbaumer et al., 2005; Peiponen et al., 2001) by exploiting a set of different immersion liquids with a priori known refractive index, and refractive index step typically 0.01. In principle injection of immersion liquid having a continuous change of refractive index could be used to identify MPs (Niskanen et al., 2010). However, because of the relatively high refractive index of plastics one would be forced to use toxic liquids that would pollute water hence such a method is not favorable. This work differs since water only is used as natural immersion liquid, and optical data in Vis is emphasized because the light is less absorbed by water, while some plastics absorb light in that region.

In optical transmission spectroscopy, which is a typical tool in materials studies, the interaction of light with media that are absorbing, homogeneous and isotropic is governed by Beer–Lambert’s law which states that, if the light beam, with intensity $I_0$, strikes the sample at one end and the light emerges on the other side of the sample with intensity $I$, then the two intensities, wavelength-dependent, of light are connected via the intensity law:

$$I(\lambda) = I_0 e^{-\alpha(\lambda)d},$$  

where $\alpha$ is the absorption coefficient, $\lambda$ is the wavelength of light and $d$ is the sample thickness. In the case of samples having surface roughness, such as rough plastics considered in this study, light scattering also affects the magnitude of the transmitted light, $I$. Thus, the $\alpha$ in Eq. (1) is replaced by $\alpha = \alpha_s + \alpha_a$, where $\alpha_a$ is the material absorption coefficient and $\alpha_s$ is the scattering coefficient which depends on surface roughness. It is possible that the absorption coefficient of a sample can be practically speaking zero, but the scattering coefficient is relatively large. For homogeneous and isotropic medium, the absorbance, $A$, can be obtained directly from the measured transmittance, $T = I/I_0$, by using Eq. (2),

$$A = \log\left(\frac{1}{T}\right).$$  

Moreover, for a known sample thickness, one can estimate the absorption coefficient by monitoring the transmittance. However, in this work, we consider plastic particles in water, which can be considered as a mixed medium. Therefore, rather than the absolute attenuation coefficient, significant for a homogeneous medium, the effective attenuation coefficient was calculated taking into account the thickness of the samples. The effective attenuation coefficient considers both the scattering and the absorption of the medium. Moreover, multiply scattered light photons can be subject to reabsorption. The effective attenuation coefficient is described by Eq. (3),

$$\alpha_{\text{eff}}(\lambda) = -\ln\frac{T(\lambda)}{d_{\text{sample}}}. $$

To study the presence of microplastics in water bodies, it is imperative to understand the optical properties of water without any impurities; this is given by Partington’s formula (Partington, 1960). In the Vis spectrum, water has negligible absorption whereas some plastics absorb light as will be seen later in transmittance data. In the latter case, some photons escape the detector, but some photons may undergo multiple scattering, having a longer optical path, before reaching the detector. Longer optical path length can lead to (increased) effective absorption (coefficient) for some plastics as will be seen from transmittance data of rough plastics. For smooth plastics in water, one can get the reflection and transmission coefficient of Vis light with the aid of ellipsometric refractive index data and Partington’s formula. However, for the rough plastics, reflection and transmission are greatly influenced by the magnitude of the surface roughness. As a result, both diffusely reflected and transmitted light are present in such a case.

3. Materials and methods

We have studied smooth and roughened plastic sheets that have a size bigger than a microplastic but are important to understand the optical properties of smooth or rough MPs having the size in the order of magnitude in sub-millimeter or millimeter. Such a choice of size is reasonable because it takes a long time before plastic takes size smaller than 1 mm in water (Julienne et al., 2019). The samples are polypropylene (PP), polyethylene terephthalate (PET), polyamide nylon 6 (PA) and polystyrene (PS), which are commercial plastics from Goodfellow, UK. The thickness values for all the plastic samples are given in Table 1. The chosen plastic types can be present, e.g. in filtered wastewater samples. To achieve the rough plastics, the smooth samples were roughened on both sides using 320 grit sandpaper with circular sanding finishing type. By sanding plastic, we simulate mechanical erosion of MP because MPs in natural water bodies are a subject of erosion that results in to increase in the surface roughness of MPs as a function of the residence time. Also, other PET samples were roughened with three different grit standards to simulate aging of MPs (Iokaimidis et al., 2016). The measured average surface roughness with a Mitutoyo stylus profilometer (J210, Japan) for the PET samples is 0.34 mm for 1200 grit, 0.60 mm for 600 grit, and 1.10 mm for 320 grit. This was necessary to simulate the case of surface wear of plastics in the aquatic environment (Lambert and Wagner, 2016) and to investigate the influence of the magnitude of the average surface roughness on the detection of the plastics in the water. With the profilometer, we scanned surface profiles from different locations from the roughened PET samples and found that the surface height distribution function follows quite nicely Gaussian statistics.

To explore the optical properties of plastics in water, the transmittance of plastic sheets, immersed in a 1 mm thick cuvette containing tap water (air-glass-water-plastic-water-glass-air) was measured with the spectrophotometer (PerkinElmer Lambda 9) in the Vis-NIR spectral range. Usually both water and plastic have strong absorption in the NIR region, hence the short path length of only 1 mm was chosen. Regarding practical implementations, the Vis region, a long optical path length, is used for the detection of the plastics in the water volume.

The scattering coefficient is familiar from typical light scattering from small particles, such as spheres, and the strength of the scattering depends on the size, the refractive index mismatch of the scattering material and the surrounding medium, and the wavelength of the probing light source. Based on the generalized Beer-Lambert’s law, there are multiple scatterings between the two rough surfaces, which causes longer optical path lengths for

| Material | Thickness (mm) |
|----------|----------------|
| PP       | 0.55           |
| PET      | 0.25           |
| PA       | 0.50           |
| PS       | 0.19           |
scattered photons. Here, we have rather used the known thickness of smooth plastics rather than the cuvette thickness of 1 mm, in the calculations to study a training set of different plastic samples of this study.

The wavelength-dependent refractive index of plastic samples (PA, PET, PP, and PS) were measured using an ellipsometer (J. A. Woollam V–VASE) in the reflection measurement mode. This refractive index was utilized together with the wavelength-dependent refractive index of water, which were extrapolated using the Partington’s formula (Partington, 1960) for comparison purposes regarding light interaction in water—plastic interface.

4. Results and discussions

4.1. Refractive index ratio

In Fig. 1 are shown the refractive index ratio dispersion curves (refractive index mismatch between plastic and water) for the different plastic samples in the Vis spectrum (580–780 nm). The curves show a monotonic decrease as the wavelength increases. Since the wavelength-dependent refractive index (Peiponen et al., 2019) is different for each plastic-type and higher than that of water, their ratios are expected to vary. Thus, the PS sample has the highest refractive index ratio followed by PET, PA, and PP. Using the refractive index mismatch data in Fig. 1, it is possible to estimate the reflection losses for each sample. Moreover, using the refractive index mismatch, in addition to surface roughness, one can understand the crucial role of light scattering which consequently affects the amount of light transmitted through plastics embedded in water.

The refractive index ratio in (Fig. 1) is one viable method for ranking different plastic types. However, natural water bodies usually contain naturally occurring marine particles, which have a refractive index closer to that of plastics. In the pioneering work of Aas (1996), the refractive index ratio of marine particles and water were studied for a few discrete wavelengths. Instead of discrete wavelengths, here, we have considered refractive index ratio for the plastic and water but in a much broader spectral range. The results obtained in the present paper show that the refractive index ratio shown in (Fig. 1) for the plastic samples tends to be larger, same, or smaller than the discrete values of (Aas, 1996), thus, showing the complexity of screening such plastics from the marine particles which are supposed to have wavelength-dependent refractive index different from that of plastics. Nonetheless, we infer that the refractive index ratio across a broader spectrum, in addition to other complementary data analyses, can still be used as one possible method for the differentiation of MPs from marine particles.

The Partington’s formula (for calculating the intrinsic refractive index of water) is valid for water at 25 °C, this might not hold for water at lower temperature and pressure such as in deep waters which require different treatment (Weiss et al., 2012). Therefore, in this work, Partington’s formula was used for simplicity. The refractive index of water depends on the density of water that in turn depends on thermodynamic variables of temperature, pressure and, in the case of, seawater the salinity. Liquid water is a special case of materials because pure water has the highest density at 4 °C and hence the highest refractive index at the same temperature for constant pressure. The refractive index of water is subject to change because of temperature variations in seas, lakes, and rivers.

The variation of water temperature leads to the variation of density and hence changes in the refractive index of plastics embedded in water (Kasarova et al., 2010). If we wish to calculate the refractive index of water in changing temperature conditions, the empirical Lorentz-Lorenz formula (Schiebener et al., 1990) is useful. It gives the refractive index of water, which is valid for the spectral range of 0.2–2.5 μm. Thus, when both temperature and refractive index are changing, the thermo–optic constant, dn/dT where T is the absolute temperature, rules the change of refractive index of plastic. If we go relatively deep in water the refractive index of water and plastic depends also on pressure, which is also one variable in the formula given by (Schiebener et al., 1990). Therefore, the refractive index results presented in this work are only qualitative but hold quite well in laboratory conditions.

4.2. Transmission spectra

In Fig. 2 the optical transmission spectra of both smooth and rough plastic samples were explored in Vis–NIR spectral range. One can observe that both pure water and the plastic in the Vis region, as compared to the NIR region, absorb less light. Moreover, the samples have different thicknesses (Table 1) which means that the transmittance of each plastic in the water is influenced by water absorption differently in the 1 mm cuvette. Considering these, we explore the transmittance in the Vis in the screening method.

We note that since the plastics have different refractive index ratio, as shown in Fig. 1 above, embedding them in the water will change the observed transmittance but the nature and appearance of bands (in the Vis-NIR) will only depend on the type of the plastic. More importantly, the rough plastic will decrease the transmittance due to the increased backscattering and multiple scattering of light. However, for each type of plastic, the fingerprints will be the same for both smooth and rough plastic as will be demonstrated below. This suggests that for short optical path length measurement configurations rough plastics can be identified by their intrinsic NIR fingerprints. As an example, the Vis-NIR transmittance curves for smooth and rough (with an average surface roughness of ca. 1 μm) for different plastic samples embedded in water are shown in Fig. 2(a–d), where the vertical dashed lines in Fig. 2(a–d) represent the different absorption bands for plastics. Liquid water (black dashed lines) has absorption bands centered at 970, 1200, 1450, and 1950 nm, which are dips seen in Fig. 2.

The nature of transmission curves for PA (Fig. 2a) is almost the same as those of PP (Fig. 2c) in the entire Vis-NIR spectral range, except that the magnitude of transmittance is slightly higher for PA. Moreover, the fingerprints in the transmittance curves also vary in position. The curves for PET (Fig. 2b) are almost similar to those of...
PS showing similar nature of deeps in the Vis-NIR spectral range with a slight difference in magnitude and position. The closeness of the optical properties of the two pairs of material is also evident in the intrinsic absorption coefficient curves in the Vis region as will be seen in the next section.

The trend of transmittance curves in the Vis region for both rough (dashed lines) and smooth (solid lines) plastics are similar for the same type of plastic, showing a rather linear behavior for both smooth and rough plastics. In Fig. 2a and c, the transmittance increases with an increase in wavelength whereas in Fig. 2b and d the transmittance is almost constant or decreases slightly with wavelength. Hence, based on the decrease in transmittance (transmittance trend), it is possible to detect and differentiate rough from smooth plastics, because the transmittance of rough samples is less than that of smooth samples. Furthermore, based on the fingerprints in the NIR region, it is possible to detect both rough and smooth plastics and differentiate those from water. We remark that in the case of a colored MP similar procedure as above can be applied in case the MP transmits light. In such a case, the color is identified by the presence of an absorption band in the Vis region. If the MP is not transmitting light, then the reflectance can instead be used for monitoring of the surface roughness. In such a case the measurement configuration is different but not difficult to achieve.

Anyhow, the object of this study is translucent MP which is more difficult to detect by an optical probe than a colored MP.

As a conclusion of the data presented above, we wish to remark that using the observed trends of transmittance in Vis we can suggest that an MP belongs to a certain class namely increasing slope of transmittance (class I), decreasing slope of transmittance (class II) or constant slope of transmittance (class III).

4.3. Intrinsic absorption coefficient

Intrinsic absorption coefficients of smooth plastics (with water as ambient medium) were calculated using Eq. (2) and transmittance data from Fig. 2. The intrinsic absorption coefficient curves for smooth plastic samples (PA, PET, PP, and PS) are shown in Fig. 3a. For these smooth samples, scattering was assumed to be negligible. From Fig. 3a, sample PP has the highest intrinsic absorption coefficient followed by PA, and corresponding curves of PP and PA follow similar monotonous decreases as wavelength increases and hence resemble each other. The curves for PS and PET have overlapping intrinsic absorption coefficients.

The absorption coefficient of rough plastics with water as ambient medium (effective attenuation coefficient) was calculated using transmittance data from (Fig. 2a and b) where $d_{\text{sample}}$ was...
taken to be the thickness of plastic cuvette. Fig. 3b shows the effective attenuation coefficient curves for plastic samples (PA, PET, PP, and PS); it is obvious that sample PP has the highest effective attenuation coefficient followed by PA while in this case, PS is slightly higher than PET.

Based on the results of Fig. 3a, b, one can conclude that the intrinsic absorption coefficient of smooth plastic samples can still be used to categorize some of the samples (PA and PP). However, the lower overlapping curves of PET and PS cannot be differentiated from one another but can be differentiated from PA and PP. On the other hand, the effective attenuation coefficient in the Vis region appears to be a better tool for separating the different roughened samples, the intrinsic absorption coefficient was chosen to be utilized in the next calculations because it is possible to create a library of intrinsic absorption coefficient as compared to roughened samples which are unpredictable.

The effect of roughness was studied to understand how the optical properties of the same plastic material in water were affected by introducing different roughness, and thus, to ascertain if this could affect the detection of plastics in the Vis region. Usually, plastic water bottles typically made from PET can experience such roughening due to mechanical erosion in water. In Fig. 4 are shown the transmittance spectra of water together with PET plastic samples for three different average surface roughness.

From (Fig. 4), we can infer that the curves are arranged in the order of descending surface roughness, thus, the sample with the lowest surface roughness has the highest transmittance while that with the highest surface roughness has the lowest transmittance. The influence of average surface roughness magnitude on the transmittance of the roughened PET in water is seen in the whole Vis-NIR range. Logically, increasing the magnitude of average surface roughness via mechanical roughening increases the light scattering (multiple in the sample volume) which correspondingly reduces the transmittance. Thus, the same plastic material will appear different in water as a result of natural roughening processes.

As was mentioned earlier, the surface height distribution function of roughened PET samples follows closely the Gaussian probability function, i.e., a normal distribution. In such a case it is possible to estimate surface roughness of a sample using the measured transmittance, following the theory given by (Niskanen et al., 2010) for Gaussian roughness distribution function as $T = T_0 \exp\left\{-\left(2\pi R_{opt} (n_{PET} - n_{Water})^2 \cos^2 \theta\right)^2\right\}$ where $T_0$ is the transmittance of smooth PET plastic, $R_{opt}$ is the optical roughness, $\theta$ is an angle that a light ray makes with respect to the optical axis of the probe light of the spectrophotometer incident on cuvette, in this case, $\theta = 0$ and $\cos \theta = 1$. The model of Niskanen suits best for cases that the average surface roughness is much smaller than the wavelength of the probe light. Furthermore, the model assumes a negligible absorption of light.

Using the model of Niskanen et al. for the maximum wavelength of the chosen spectral band, namely 780 nm, we solved $R_{opt}$ from the data of Fig. 4. In the calculations, we used the transmittance value of the smooth PET at 780 nm as a reference. Calculated values are plotted in Fig. 5 against the measured $R_a$ in air (with the profilometer). For relatively low average surface roughness, there is nice linear relation but for the highest $R_a$ value, the linearity is no more valid. This is probably because the effective surface
roughness, \((n_{\text{PET}} - n_{\text{Water}})Ra\), is relatively close to 780 nm and the assumption of Niskanen et al. model is not fulfilled. Moreover, in a general case, the surface height distribution function may be non-Gaussian and the MP may be curved, in such cases the model may fail. Nevertheless, the results for moderately rough PET samples in Fig. 5 are promising regarding the detection of surface roughness of a flat MP in an aquatic environment. Additionally, the detected transmittance of rough plastics is already a nice measure of the presence of a rough translucent plastic object and such a transmittance is a rather general quantity to monitor surface roughness because it is not based on any assumption of the probability function of the surface statistics. For practical implementation of this concept on the field, one can exploit commercially available miniaturized spectrophotometers that provide instantly a spectrum without time-consuming wavelength-scanning of conventional laboratory spectrophotometers. The diameter of the probe beam of the device can be reduced to detect relatively small size MPs. Such a device modified to operate standalone in the aquatic environment or installed in a ship that is monitoring MPs at different places could be useful for the estimation of surface roughness and sorting of MPs.

![Fig. 5. The plot of optical roughness (Ropt) against real roughness (Ra).](image1.png)

![Fig. 6. Plastic thickness curves in part of Vis spectral region for, (a) Smooth plastics with smooth intrinsic PS as reference, (b) Rough plastics with own intrinsic smooth plastic reference, (c) Rough plastics with intrinsic smooth PS as reference, (d) Various rough PET with intrinsic PET reference.](image2.png)
4.4. Thickness

As an interesting tool for analysis, the absorbance in Eq. (2) and the intrinsic absorption coefficient of Fig. 3a were utilized to obtain the thickness of plastic samples in water. To utilize the thickness for analysis, it is assumed that we have the library of intrinsic absorption coefficients of different plastics in water, and such a library can be extended to other transparent plastics. This library can be used both for the identification and detection of the presence of rough plastics. In Fig. 6(a–d) are shown the calculated thicknesses for different plastic samples in the Vis spectral region using Eq. (3). The resulting thickness values of (Fig. 6a) were obtained as the ratio of other different smooth plastic samples with smooth PS as reference. If the comparison is made between the results of Fig. 6a and c with the results of Table 1, it can be concluded in both cases that the curve for sample PP (with bigger thickness) has a higher magnitude followed by PA, while samples with small thickness values namely, PET and PS have curves with smaller magnitudes.

For the case of Fig. 6b (rough plastics each with same type plastic reference), one can observe a different trend for the curves. Samples PA and PP have almost overlapping curves in the Vis region, however, the thickness value, in this case, is slightly above 1 mm and slightly increases with wavelength showing abnormality. Similarly, PS and PET have abnormal and even higher thickness values as compared to the former samples. In Fig. 6c (rough plastics with smooth PS reference), one can observe varying curves and abnormal thickness values for all the samples. In Fig. 6d is shown the curves for PET samples with different roughness values, from the curves one can observe an inverse relationship between thickness and roughness, and the thickness values for all the samples are abnormal. It is clear from Fig. 6d that both samples show abnormal thickness value, and this differentiates rough from smooth plastics.

In both cases Fig. 6(b–d), we get the abnormal thickness value in comparison with true thickness except for certain curves in Fig. 6a where there is correct intrinsic absorption coefficient and smooth samples PS and PET. Even in the case of the correct intrinsic absorption coefficient but the rough sample, we get abnormal thickness and the apparent change of thickness as a function of the wavelength of the probe light. Thickness cannot vary as a function of wavelength therefore, the abnormal change is evidence that either wrong intrinsic absorption coefficient was used, or rough plastic samples are detected. Therefore, by utilizing the library of intrinsic absorption coefficients and the measured transmittance spectra of water inside the cuvette containing a microplastic, it is possible to detect the presence of rough and smooth MP and possible to predict the type of MP.

The flowchart in Fig. 7 is a summary of this work. We start with a library of intrinsic absorption coefficient (α) of different plastic samples, next transmittance is measured in 500–780 nm followed by the refractive index measurement. The calculation of thickness is done, this is a novel feature. In the case of a smooth plastic sample, this is identified because the result is constant thickness as a function of wavelength. However, if after using all intrinsic absorption coefficients of the library instead we get the thickness that depends on the wavelength, we deduce that we have found a rough plastic sample. The combination of the trend of transmittance and thickness value is utilized to rank plastic to a certain class and possibly type of MP. Moreover, the average surface roughness of plastics is determined by using the transmittance and refractive index.

5. Conclusions

In this work, we have investigated roughened plastic samples, and have shown that it is possible to detect and identify rough plastic sheets that are either transparent or translucent in water volume, using the trends of transmittance in Vis-NIR spectral region, dispersion, absorption, and thickness value in the Vis region. The use of transmittance trends in the Vis spectral range for the in-
situ detection of plastics in an aquatic environment is promising and pave a way towards the designing and development of cheap and portable optical sensors due to the low absorption of water and the availability of cheap silicon detector in the Vis range. Moreover, we have also shown that it is possible to qualitatively estimate the average surface roughness of plastic sheets/films using their transmittance and refractive index. Are novel features in the detection of MP in an aquatic environment since one cannot obtain this information from other existing optical techniques such as FTIR and Raman. Here, we present a relatively simple method to obtain information on the effective surface roughness of MP which is crucial in the determination of MP aging, due to erosion and the estimation of surface contamination by the adsorption inorganic and organic particles such as bacteria.

CRediT authorship contribution statement

Boniphace Kanyathare: Conceptualization, Methodology, Formal analysis, Visualization, Validation, Writing - original draft, Writing - review & editing. Benjamin O. Asamoah: Investigation, Visualization, Writing - review & editing. Umair Ishfaq: Conceptualization, Investigation. James Amono: Investigation, Writing - review & editing. Jukka Raty: Investigation, Writing - review & editing. Kai-Erik Peiponen: Conceptualization, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing.

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