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Research Paper

A microwave-based technique as a feasible method to detect plastic pollutants in experimental samples

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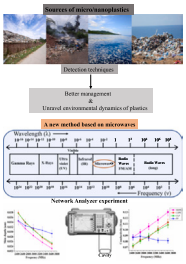
HIGHLIGHTS

- Environmental pervasiveness of plastics warrants efficient detection methods.
- Plastic detection method based on electrical characteristics is demonstrated.
- A feasible, quick non-destructive measurement method using microwave frequencies.
- Absorption factor, dielectric constant, and dielectric loss tangent are useful parameters.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic-derived pollutants are hazardous and pervasive in the environment, and their detection is a challenge due to observational constraints of various dimensions. Physical, chemical, thermal, and spectroscopic methods are extensively used to identify microplastics in environmental systems, but fundamental challenges exist in the isolation and analysis of nanoplastics from environmental samples. The promising practices are often destructive, rendering the samples inutile for further investigations. In this paper, a technique based on the measurement of the dielectric properties of the samples, carried out using the rectangular cavity perturbation technique at the S-band of microwave frequency of 2–4 GHz is proposed. The ability of this method to identify some of the most abundant types of plastics found in the environment, polypropylene, low-density polyethylene, high-density polyethylene, and cross-linked polyethylene, is demonstrated. Electrical characteristics at microwave frequencies such as absorption factor, dielectric constant, and dielectric loss tangent are found useful in the identification of various polymers in the samples. Further, this method can be applied to identify other environmentally stable performance and engineering polymers, which are not often investigated in the environmental matrices for their hazardous effects. This non-destructive measurement method is quick and straightforward and can be further developed to identify a wide range of plastic materials present in various environmental compartments.

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1. Introduction

Plastic pollutants, namely micro (< 5 mm) and nanoplastics (upper size limit at either 100 nm or 1000 nm) (Gigault et al., 2021), have infiltrated the earth's environmental compartments and are recently being detected in various biological and ecological realms. This is primarily due to the revived interest among the research community to study the local, regional, and global environmental impacts of plastic pollutants and the recent development of efficient techniques for detecting plastics in environmental matrices. Recent investigations have revealed that plastic constituents are present in crop plants (Li et al., 2020), flowering plants (Sun et al., 2020), and edible fruits and vegetables (Conti et al., 2020). They are also found in fish (Jacob et al., 2020), penguins (Le Guen et al., 2020), and sea birds (Padula et al., 2020). Emerging reports of the presence of monomers or plastic constituents in human organ and tissue samples (ACS, 2020) and the recent detection of polypropylene microplastic particles in the human placenta (Ragusa et al., 2021) show the magnitude of the pervasiveness of the plastic problem in the biosphere. Plastic derivatives are detected even in difficult-to-access geographical domains such as Arctic snow (Bergmann et al., 2019), Antarctic sea ice (Kelly et al., 2020), the deepest ocean trenches (Jamieson et al., 2017), pristine mountains (Allen et al., 2019) and the remotest islands (Lavers et al., 2019).

Efficient detection and analysis methods are necessary to effectively address and manage these emerging problems in the biosphere. Various methods have been developed for plastic detection in environmental samples in recent years. Identification and quantification of plastics were mainly carried out by visual, spectroscopic, and spectrometric techniques and modeling analysis (F. Wang et al., 2021; X. Wang et al., 2021). Comprehensive reviews enumerating various methodologies for plastic detection in different environmental compartments (Prata et al., 2019; Elkhatib et al., 2020; Huang et al., 2020; Kwon et al., 2020; Castelvetro et al., 2021; F. Wang et al., 2021; X. Wang et al., 2021) have been carried out lately. There are some promising advancements in detecting plastic pollutants and pollutants associated with them in the environmental matrices. Recently, submicrometer-sized plastic pollutants in water were detected using nanostructured Raman substrates (Lê et al., 2021). Soxhlet and ultrasound-sssisted extraction techniques are used to extract organic pollutants adsorbed on microplastics, and gas chromatography with different detectors is the most used quantification technique for pollutants adsorbed on microplastics (Santana-Viera et al., 2021). Terahertz time-domain spectroscopy can be used in aiding the detection of microplastic embedded in table salts (Im et al., 2021). The terahertz spectrum combined with the least squares support vector machine algorithm is a promising technique for rapidly detecting microplastics in soil (B. Li et al., 2021; Y. Li et al., 2021). A recent, state of the art review discussed advantages and limitations of various advanced methods, and their complementarity for the comprehensive characterization of microplastics (Ivleva, 2021). Most of the prevailing plastic identification techniques are quite expensive and time-consuming (Kurniawan et al., 2021). Energy and resource pre-requisites are also high for many currently used identification and detection techniques. As the amount and diversity of plastic infiltration into environmental compartments and their impacts are increasing, there is a need for more energy-efficient, fast, and economically feasible techniques. Considering these facts, we explore the feasibility of employing microwaves to identify and detect smaller counterparts of plastic pollutants widely present in environmental compartments. Though there are various detection techniques, a fully-fledged microwave-based method for detecting plastics has not yet been devised or tested.

The microwave method described in this paper has been developed to detect plastics in experimental samples for the first time to the best of our knowledge. The technique will be an addition to the existing methodologies utilizing the potential of microwave radiation. The present study uses dielectric properties/complex permittivity of plastic samples at microwave frequencies, a hitherto undescribed method to detect plastic pollutants in samples. In terms of environmental plastic detection, an all-encompassing method suitable for different compartments and material mediums has not yet materialized irrespective of a multitude of environmental plastic studies in recent years. The microwave method can be molded into various best-fit applications suitable to different environmental realms and mediums. In addition to this, the knowledge and experiences from well-developed fields of diagnostics and detection sciences using microwaves can be integrated into the environmental detection of emerging contaminants. The method discussed in this paper is suitable for various mediums such as air, water, soil, and biological materials, including fluids. It is expected that the methodology described in this paper can trigger the development of genera of methods utilizing microwave properties in detecting various types of polymers present in the environmental matrices.

2. Materials and methods

2.1. Microwave characteristics and their applications

Electromagnetic radiation has an electric and magnetic field component that oscillate in phase perpendicular to each other and the direction of energy propagation (Freeman et al., 2019). Electromagnetic radiation is classified according to the frequency (or wavelength) of the wave as radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. Here, radio waves have the longest wavelengths (the lowest frequency), and Gamma rays have the shortest (the highest frequency). Microwave radiation has frequencies between 300 MHz and 300 GHz (corresponding wavelength range- 1 m to 1 mm). From a radio-frequency engineering perspective, the microwave frequency band usually ranges from approximately 1 GHz to 100 GHz (Karmel et al., 1998).

Microwave capabilities are widely utilized in various scientific and technological fields. For example, microwave processing is used to improve the physical properties of processed materials. Comparatively, less energy and time are required during microwave processing and reduced chances of degradation that may occur with conventional heating methods, which heat from the outside. For example, microwave energy is derived from electrical energy with a conversion efficiency of approximately 50% for 2450 MHz and 85% for 915 MHz (Ran et al., 2019). Reduced processing time and energy used are due to rapid volumetric heating caused by microwave irradiation. The material heats quickly through rapid dipole reorientation (Metaxas and Meredith, 1983). The major characteristics of microwave heating are penetrating radiation, rapid heating, controllable electric field distributions, selective heating of materials, and self-limiting reactions (Vasudev et al., 2019), which cannot be accomplished with convection heating.

Microwave technologies have huge global economic implications as they are used for oil, gas, and mineral explorations (Lipton and Gubins, 1997; Mutyala et al., 2010). Microwave radiation properties are used to study and understand various planetary phenomena and learn more about the universe. Astronomers use microwaves for understanding various astronomical phenomena as molecular clouds, stars, galaxies, and other astronomical objects emit microwaves. The composition of a star or gas cloud, their temperature range, and movement can be predicted by analyzing the emitted microwave radiation (Jansky, 1933). Further, cosmic background radiation is most easily detected in the microwave region, and it is also called microwave background radiation (Hey, 1983).

Microwave-based techniques are widely used in medical sciences in the therapeutic and diagnostic fields (Lonappan, 2010). Under a controlled environment, microwave-generated heat can have a therapeutic effect on several ailments. Microwave diathermy is used to treat arthritis, joint and circulatory problems, relieving the pain, bacterial infection, septic fingers, boils, abscess, and dysmenorrhea. A more promising use of microwaves is in the treatment of cancer.

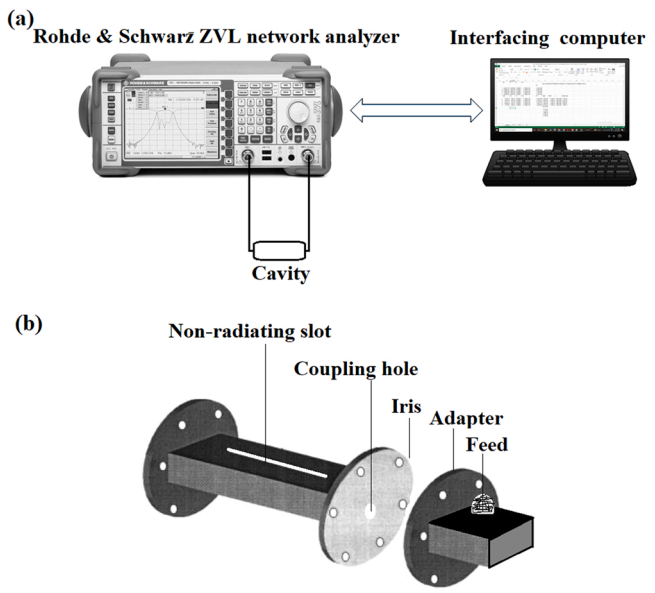

Fig. 1. a) Schematic diagram showing the experimental set-up involving a network analyzer and b) structure of the cavity which act as sample holder.

Microwave-assisted balloon angioplasty is the technique of mechanically widening a narrowed or obstructed blood vessel, typically due to atherosclerosis (Paolella and Lexa, 2006). Microwaves are also used to treat a condition called atrial fibrillation, where the heart's chambers beat irregularly (Schuetz et al., 2003). The use of microwaves in the diagnostic field show promise in detecting and locating tumors and brain injury detection (Islam et al., 2019; B. Li et al., 2021; Y. Li et al., 2021). Microwave ablation is a promising development in tumor ablation, and the technique allows for flexible approaches to treatment, including percutaneous, laparoscopic, and open surgical access. The technique also has promising potential in treating primary and secondary liver disease, primary and secondary lung malignancies, renal and adrenal tumors, and bone metastases (Simon et al., 2005). The microwave-based methods were used successfully in the study of cholesterol in blood samples (Lonappan, 2012a, 2012b), assessment quality of food items (Lonappan et al., 2017), and disease-causing agents in human blood (Lonappan et al., 2009; Lonappan, 2012a, 2012b).

Microwave technology is also considered environmentally friendly, though contrasting views exist. Microwave technologies for industrial, scientific, and medical (ISM) purposes are associated with various aspects of environmental protection, sustainable economic growth, healthcare, and the achievements of science and technology (Komarov, 2021). It is also proposed that microwave-based synthetic routes for the synthesis of green technology products will be a step toward sustainable development (Sreerenjini et al., 2021). Applications of the microwave technology are mainly divided into two categories: information and energy. The information category involves radar applications as well as communication applications. Industrial, scientific, and ISM applications are included in the energy category. The most common utilized frequency for home applications, for example, microwave oven, is 2.45 GHz. Frequency bands reserved for industrial applications are 915 MHz, 2.45 GHz, 5.8 GHz, and 24.124 GHz (Ku et al., 2001). Microwave radiation is also used to investigate the electro-physical properties of different materials ranging from dielectrics to superconductors (Laurinavicius et al., 1987).

2.2. Sample preparation and experimental set-up

The study was conducted on plastic samples, locally sourced from plastic vendors in Mumbai, India, which were low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and cross-linked polyethylene (CLP). These plastics are the most detected in various environmental compartments and biological realms (Geyer et al., 2017; Chae and An, 2018; VishnuRadhan et al., 2019; Amato-Lourenço et al., 2021; VishnuRadhan et al., 2021; F. Wang et al., 2021; X. Wang et al., 2021). The samples were analyzed in powdered form and were white-yellowish except for CLP, which had particles in three colors, blue, black, and white. The CLP samples were analyzed separately for different colors, but the results were almost similar. The results reported here used white CLP samples. Altogether ten samples (five dry and five wet) were analyzed, three times for each sample. Wet samples were prepared by spiking the dry samples with distilled water. The samples were filled in the capillary bulb for microwave measurements, and the measurements were made at 20 °C. The primary component of the measurement set-up (Fig. 1) was a transmission type S-band rectangular cavity resonator, which was a transmission line on or both ends closed attached to a Rohde & Schwarz ZVL network analyzer set-up (Fig. 1a). A network analyzer is usually used to measure the network parameters of electrical networks. We have utilized its capabilities to set up a measurement method for detecting plastic pollutants in the environmental samples.

Fig. 1b shows the details of the brass cavity sample holder. The transverse electric ($TE_{10\rho}$) mode excitation was carried out on the resonator. A capillary glass tube splayed to a disk-shaped bulb at the bottom was employed as the sample holder. The length of the resonator determines the number of resonant frequencies. The sample holder was placed on the broader side of the cavity through the non-radiating cavity slot enabling its effortless motion inside the cavity. Firstly, the empty sample holder was placed in the cavity. The resonant frequency (f_o) and the associated quality factor (Q_o) were measured at the maximum electric field. The second step was to fill the empty sample holder with a known amount of sample under investigation. After placing it into the cavity resonator, the sample's position was adjusted inside the cavity for the maximum resonant frequency shift with a minimum amplitude for the peak. This adjustment for attaining maximum perturbation was made after selecting the resonant frequencies of the cavity. Similar to the first step, the resonant frequency of sample (f_s) and the corresponding quality factor (Q_s) were measured. Q_s and f_s were measured when the cavity was loaded with the sample containing capillary. This procedure was carried out for other resonant frequencies in the S-band of the microwave region of the electromagnetic spectrum from 2 to 4 GHz.

2.3. Theory behind the experimental set-up

2.3.1. Determination of complex permittivity using a rectangular waveguide cavity

The empty cavity (without sample) has the electric field E_0 and magnetic field H_0 in an unperturbed state, where the interior fields are E and H. Following Maxwell's equations and an equation for the resonant frequency shift (Bethe and Schwinger, 1943), Eq. (1) (Harrington, 1961) shows the variation of resonant frequency for lossless sample:

$$\frac{\omega-\omega_0}{\omega}=-\frac{\int\left(\Delta\varepsilon E\cdot E_0^*+\Delta\mu H\cdot H_0^*\right)d\tau}{\int\left(\varepsilon E\cdot E_0^*+\mu H\cdot H_0^*\right)d\tau} \tag{1}$$

where, ε is the permittivity of the medium in the unperturbed cavity, μ is the permeability of the medium in the unperturbed cavity, $d\tau$ is the elemental volume. $\Delta\varepsilon$ and $\Delta\mu$ are the changes due to the introduction of the sample (in the cavity) in permittivity and permeability, respectively.

For a lossy sample, the complex frequency shift (Waldron, 1960, 1969) without affecting the generality of Maxwell's equations is given in Eq. (2):

$$-\frac{\delta\Omega}{\Omega}\approx\frac{\left(\bar{\varepsilon}_r-1\right)\varepsilon_0\int_{V_s}E\cdot E_0^*dV+\left(\bar{\mu}_r-1\right)\mu_0\int_{V_s}H\cdot H_0^*dV}{\int_{V_c}\left(D_0\cdot E_0^*+B_0\cdot H_0^*\right)dV} \tag{2}$$

where, $d\Omega$ is the complex frequency shift, B_0, H_0, D_0 and E_0 are the fields in the unperturbed cavity. $\bar{\varepsilon}_r = \bar{\varepsilon}_r^{/} - j\bar{\varepsilon}_r^{//}$ and $\bar{\mu}_r = \bar{\mu}_r^{/} - j\bar{\mu}_r^{//}$ are the relative permittivity and relative permeability, respectively. V_c and V_s are the volumes of the cavity and sample, respectively.

Eq. (2) is employed considering the approximations that the fields in the empty part of the cavity are unaffected or negligibly changed by sample insertion. The fields in the sample are assumed to be uniform over their volume. These approximations are valid when the introduced sample or object in the cavity is relatively smaller than the resonant wavelength. The resonant frequency is lowered when the sample is introduced into the cavity, which is indicated by the negative sign in the Eq. (2). The numerator represents the energy stored in the sample, and the denominator represents the total energy stored in the cavity. The total energy is represented by Eq. (3) given below,

$$W = W_e + W_m = 2W_e = 2W_m. \tag{3}$$

When a dielectric object or sample is introduced into the cavity at the maximum electric field, a slight change in ε at a point of the zero electric field or a small change in μ at a point of the zero magnetic field does not alter the resonance frequency rendering only the first term in the numerator as significant. Considering this fact, Eq. (2) can be reduced as follows:

$$-\frac{\delta\Omega}{\Omega} \approx \frac{\left(\bar{\varepsilon}_r - 1\right)\int_{V_s} E\cdot E_{0\,\max}^{*} dV}{2\int_{V_c} |E_0|^2 dV} \tag{4}$$

Let the quality factor of the cavity in the unperturbed condition is Q_0 and the quality factor of the cavity loaded with the object is Q_s. The

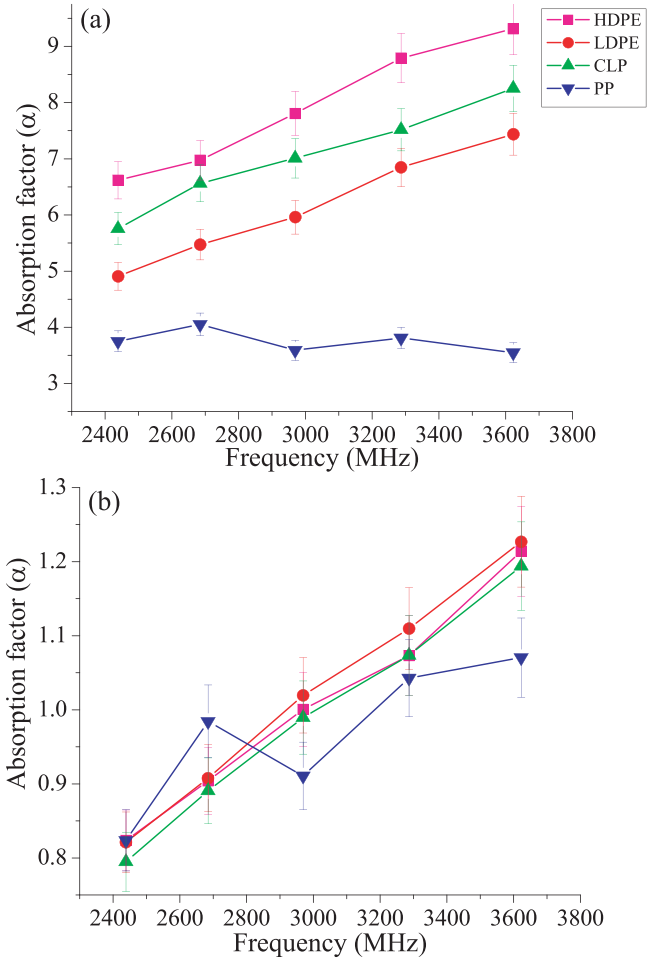

Fig. 2. Absorption factor of the a) dry and b) wet samples.

complex frequency shift is related to measurable quantities (Waldron, 1969) given by the following Eq. (5).

$$\frac{\delta\Omega}{\Omega} \approx \frac{\delta\omega}{\omega} + \frac{j}{2}\left[\frac{1}{Q_s} - \frac{1}{Q_0}\right] \tag{5}$$

Equating the real and imaginary terms of Eqs. (4) and (5), the following Eqs. (6) and (7) are obtained

$$-\frac{(f_s - f_0)}{f_s} = \frac{\left(\varepsilon_r^{/} - 1\right)\int_{V_s} E\cdot E_{0\,\max}^{*} dV}{2\int_{V_c} |E_0|^2 dV} \tag{6}$$

$$\frac{1}{2}\left[\frac{1}{Q_s} - \frac{1}{Q_0}\right] = \frac{\varepsilon_r^{//}\int_{V_s} E\cdot E_{0\,\max}^{*} dV}{2\int_{V_c} |E_0|^2 dV} \tag{7}$$

It is assumed here that $E \approx E_0$ and, E_0 in TE_{10p} mode as Eq. (8).

$$E_0 = E_{0\,\max} Sin\left(\frac{m\prod x}{a}\right) Sin\left(\frac{p\prod z}{d}\right) \tag{8}$$

where a is the broader dimension of the waveguide and d is the length of the cavity.

Further, the following Eqs. (9) and (10) are obtained by integrating and rearranging the equations mentioned above.

$$\varepsilon_r^{/} - 1 = \frac{f_0 - f_s}{2f_s}\left(\frac{V_c}{V_s}\right) \tag{9}$$

$$\varepsilon_r^{//} = \frac{V_c}{4V_s}\left[\frac{1}{Q_s} - \frac{1}{Q_0}\right] \tag{10}$$

When the frequency shift is obtained from the resonance frequency (f_t) of the cavity loaded with the empty holder rather than that with the empty cavity alone, the above equations can be re-structured into Eqs. (11) and (12).

$$\varepsilon_r^{/} - 1 = \frac{f_t - f_s}{2f_s}\left(\frac{V_c}{V_s}\right) \tag{11}$$

$$\varepsilon_r^{//} = \frac{V_c}{4V_s}\left[\frac{1}{Q_s} - \frac{1}{Q_t}\right] \tag{12}$$

where Q_t is the quality factor of the cavity loaded with an empty holder.

2.3.2. *Determination of conductivity of the materials*

The Ampere's law in phasor form for a dielectric material having non-zero conductivity is represented by Eq. (13) (Lonappan et al., 2017):

$$\nabla \times H = \left(\sigma + j\omega\bar{\varepsilon}\right)E = \left(\sigma + j\omega\varepsilon^{//}\right)E + j\omega\varepsilon^{/}E \tag{13}$$

where $\varepsilon = \varepsilon^{/} - j\varepsilon^{//}$ is the absolute permittivity of the medium.

The loss tangent is represented by the Eq. (14):

$$\tan\delta = \frac{\sigma + \omega\varepsilon^{//}}{\omega\varepsilon^{/}} \tag{14}$$

Where tan δ is the dielectric loss tangent. For dielectrics, the conductivity, $\sigma = 0$. Then Eq. (14) can be represented as:

$$\tan\delta = \frac{\varepsilon^{//}}{\varepsilon^{/}} \tag{15}$$

Where, $\sigma_e = \sigma + \omega\varepsilon^{//}$ is the effective conductivity of the medium.

But tan δ is also the inverse of Q_m which is the loaded Q-factor of the cavity with only the sample.

$$\tan\delta = \frac{1}{Q_m} = \left[\frac{1}{Q_s} - \frac{1}{Q_t}\right] \tag{16}$$

$$\sigma_e = \frac{\omega\varepsilon^{/}}{Q_m} = \frac{\omega\varepsilon_r^{/}\varepsilon_0}{Q_m} \tag{17}$$

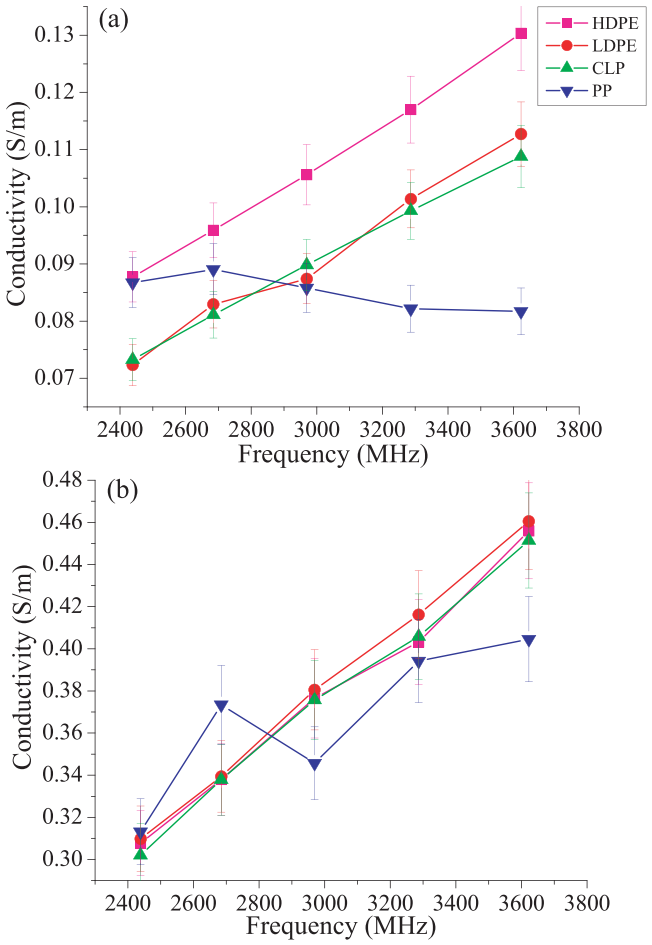

Fig. 3. Conductivity of the a) dry and b) wet samples.

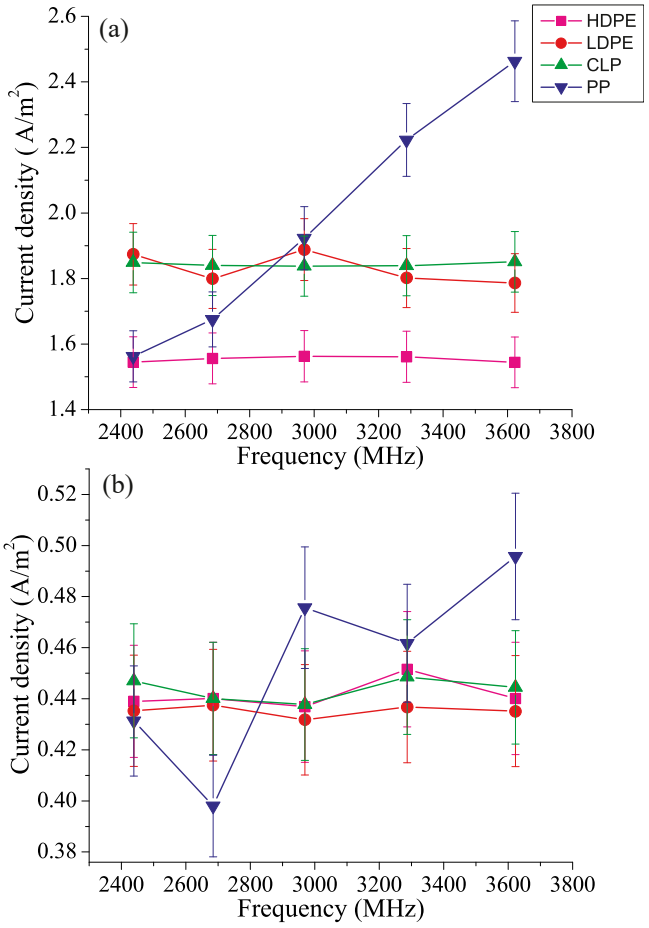

Fig. 4. Current density of the a) dry and b) wet samples.

When σ is very small, σ_e is reduced to Eq. (18).

$$\sigma_e = \omega\varepsilon'' = 2\pi f \varepsilon_0 \varepsilon_r'' \tag{18}$$

3. Results and discussion

The feasibility of using output parameters from experiments such as absorption factor (α), conductivity (σ), current density (J), dielectric constant (k), skin depth (δ), and dielectric loss tangent (tan δ) is explored for detecting plastic pollutants in experimental samples. The amount of electromagnetic waves absorbed when they pass through a medium is represented by α, which gives the measure of absorption and propagation of waves. The penetration depth (δ) is the effective distance of penetration of electromagnetic waves into the material, and by definition, it is the inverse of α (John et al., 2007). Tan δ of a material indicates dissipation of electrical energy quantitatively due to different physical processes such as dielectric resonance, dielectric relaxation, electrical conduction, and loss from non-linear processes (Sebastian et al., 2017). Here, k is also known as relative permittivity as it is measured relatively from the permittivity of free space.

Plastics can be classified as polar and non-polar plastics (McKeen, 2017). Polar plastics do not have a fully covalent bond and are conductive relative to non-polar due to their dipole moment. Some examples are polycarbonate, polyvinyl chloride (PVC), nylon, and polyethylene terephthalate (PET). Due to their conductive nature compared to non-polar plastics (which have high resistivity and a low dielectric constant), the electrical properties can have variations substantial enough to measure appropriately. The insulating nature of non-polar plastics (for example, polystyrene, polyethylene, PP) and their relative abundance in the environment compared to polar plastics prompted this investigation to explore non-polar plastics specifically. It has also incited to understand their potential to get detected through electrical and microwave techniques, which are not yet established practices to detect plastic pollutants in experimental and environmental samples.

Dry samples have higher α values (Fig. 2), which seem to decrease in wet samples. The water content can influence the absorption of microwaves, and hence the wet samples show lower values of α. The HDPE, LDPE, and CLP values are in a narrow range because the base material for these polymers is the same (PE). This implies that α cannot be employed for differentiating between various types of PE. The α for PP in the dry samples was between 3 and 4, and in the wet sample was between 0.8 and 1.15. The clustering of α values in a narrow range makes it difficult to differentiate between polymers in the wet samples. However, α can be utilized to detect polymers in the dry samples. Conductivity (Fig. 3) followed a similar suite as α, and the pattern is almost identical for both the parameters at considered frequencies. The wet samples showed a drastic increase in conductivity at all frequencies. This is due to the conducting nature of water and when the medium is other than water, the conductivity follows the suite of the medium. The PP samples showed a noticeable decrease and a steep rise in α and σ at 3000 MHz. This can be attributed to the specific material properties of PP at microwave frequencies. Conductivity ranged between 0.07 and 0.125 in the dry samples and 0.30 – 0.45 in the wet samples. The lowest current density (Fig. 4) among the dry samples was observed in HDPE, but this pattern changes in the wet samples, which are medium-dependent. The electrical properties of the polymer influence the current density at specific microwave frequencies. Unlike the steady increase in current density with increasing frequency in PP, the wet samples showed an irregular pattern of current densities with increasing frequencies.

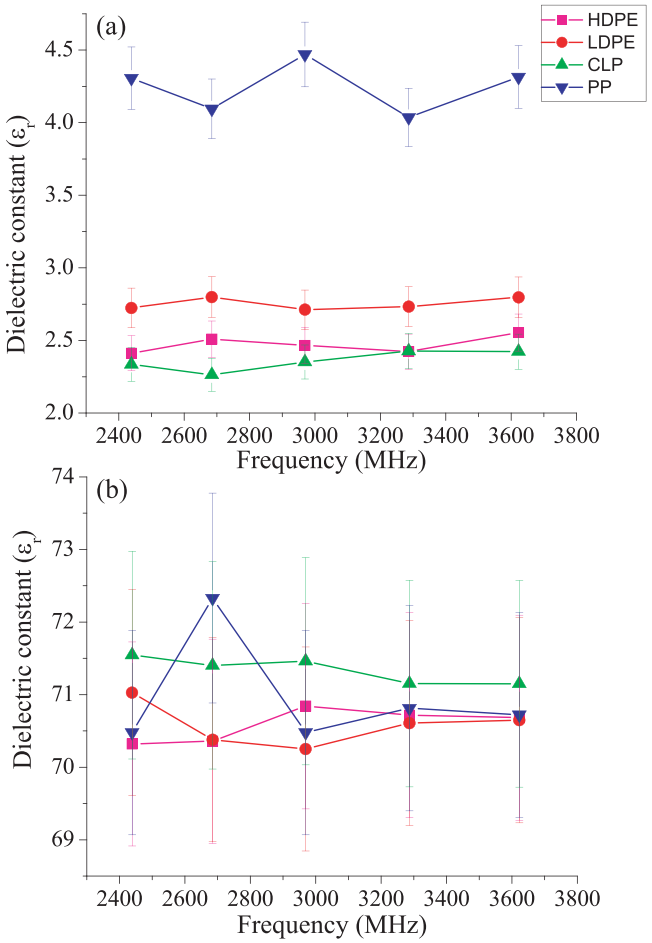

Fig. 5. Dielectric constant of the a) dry and b) wet samples.

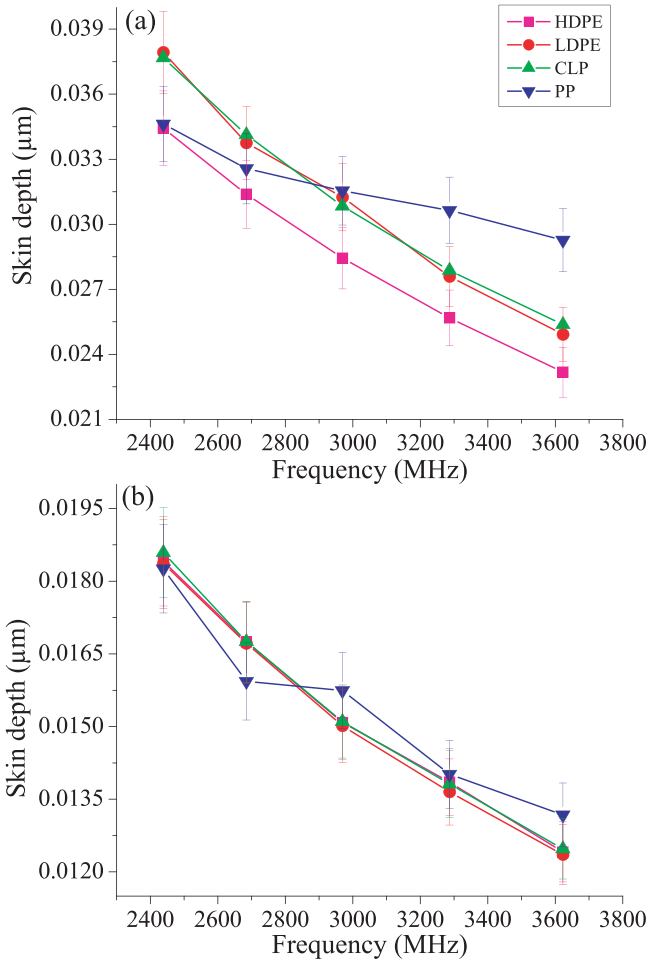

Fig. 6. Skin depth of the a) dry and b) wet samples.

The wet (dry) samples show high (low) dielectric constant values (Fig. 5) due to the non-polar nature of the plastic samples. The dielectric constant is observed to be one of the parameters that can help differentiate between various polymers in the wet and dry samples. However, notable differences in dielectric constant between the plastic types are prominent in the wet samples. The dry samples showed similar patterns of k for the PE group at all frequencies, which depend on the electrical properties of the ethylene group of polymers. The δ showed a similar pattern in both the dry and wet samples (Fig. 6), indicating that the medium did not have much influence on the patterns here. The δ values are clustered very near each other at all the frequencies rendering this parameter not much helpful in differentiating between the selected plastic samples. The tan δ showed recognizable patterns for all the dry plastic samples (Fig. 7), but the influence of the medium is evident in the wet sample patterns. Thus, this parameter is specifically helpful for analyzing the dry samples. The tan δ values were observed to be clustering around a narrow range (0.31–0.325) in the PE group in the wet samples.

The α and tan δ can be used to differentiate between different types of plastic pollutants in samples. The k can be used to identify various types of plastics in both dry and wet samples. The largest market shares belong to low-cost, commodity thermoplastic polymers such as PET, PE, PVC, PP, and PS (Chamas et al., 2020), rendering them extensively detected in the environment and subsequently well-studied. The described method can also be developed further for detecting other polymer types widely used for consumer and industrial purposes and are less studied for their environmental presence and impacts. Fig. 8 shows various classes of plastics, their properties, and their applications. Commonly detected plastics in the environment have physical properties relatively feeble than industrial and high-performance plastics. As one moves up the pyramid of plastic performance, the plastics become sturdier and more durable. This implies that once these high-performance and industrial-grade plastics find their way into various environmental compartments, they degrade at an even significantly slower pace compared to widely detected consumer plastic pollutants.

Currently, environmental impacts and the pattern of temporal and spatial distributions of high-performance plastic pollutants are largely unknown. Still, the challenges they pose are even grander than those posed by the common plastic pollutants. The ever-growing high-performance and industrial-grade plastic industries and their endless applications warrant effective and efficient methods to detect their environmental presence as well. The microwave method and derived parameters are promising for developing the technique described in this paper to detect consumer, industrial, and performance plastic particles in environmental compartments. The present study addressed non-polar plastic samples, and we will address the behavior of polar, engineering, and high-performance polymers in future studies. Further, we plan to have an open-source library of properties measured using the microwave method at various frequencies exclusively for the wide range of plastic pollutants present in environmental compartments similar to the spectral library of polymers and chemicals. This will help other researchers use the described method to quickly detect and identify hazardous plastic pollutants and their environmental pervasiveness. The technique described in this paper can be further improved and has enormous industrial-scale application potential. The method is appropriate for devising portable microwave instruments for detecting environmental plastic pollutants. We also expect these instruments to be

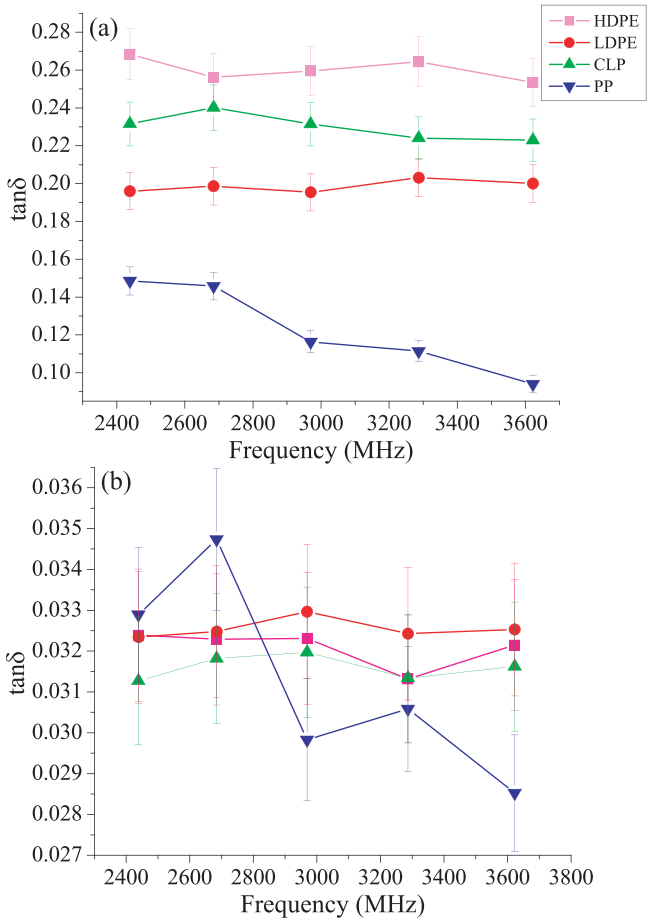

Fig. 7. Tan δ of the a) dry and b) wet samples.

economically feasible, energy-efficient, handy, and less resource-intensive.

The measurement of electrical characteristics of a material depends on various factors, for example, the microwave frequency range used and such as the nature of the sample. The technique is a feasible and efficient option as it requires only a minute volume of any sample for the measurement (Mathew, 2005). The technique is apt in the case of environmental samples of plastic pollutants that are often retrieved in minute quantities. Also, the method is non-destructive compared to many prevailing plastic detection techniques, which render the sample intact post measurements. Having discussed the merits of the microwave-assisted method in detecting plastic pollutants, some lacunae need to be addressed and understood before developing the method into a mainstream analysis method. We have not tested this method using real environmental samples, which we intend to carry out in the future with some improvements on the present method considering other frequencies and polymer types from different environmental compartments and biological entities. Also, this method can only be used in the case of small quantities of samples. That is, the volume of the sample to cavity volume is in the order of 1:1000. The measurement can be performed at the resonance frequency (2–4 GHz) of the selected cavity, not all the frequencies.

4. Conclusions

The microwave characterization of experimental plastics samples is carried out using a network analyzer using the cavity perturbation technique. We have conducted experiments to measure the electrical characteristics of the plastic samples at microwave frequencies. Various characteristics such as absorption factor, conductivity, current density,

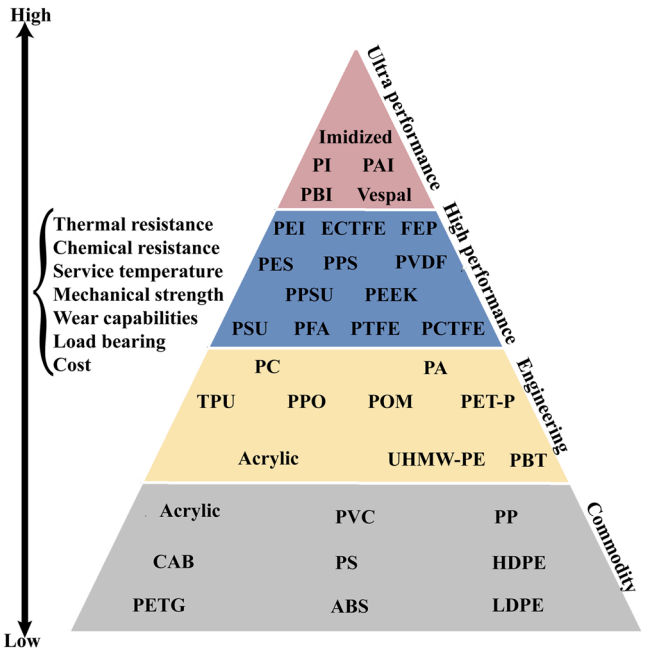

Fig. 8. Plastic performance pyramid based on properties and applications (modified from Rezakazemi et al., 2018; Friedrich, 2018; https://divplast.com/plastics-material-selection), CAB-cellulose acetate butyrate, PET-G- polyethylene terephthalate glycol, PVC- polyvinyl chloride, PS-polystyrene, ABS-acrylonitrile butadiene styrene, PC-polycarbonate, PA-polyamide, TPU-thermoplastic polyurethane, PPO-poly(p-phenylene oxide), POM-polyoxymethylene, PET-P-polyethylene terephthalate, UHMW-PE-ultra high molecular weight polyethylene, PBT- polybutylene terephthalate, PEI-polyetherimide, ECTFE- ethylene chlorotrifluoroethylene, FEP-fluorinated ethylene propylene, PES-polyethersulfone, PPS-polyphenylene sulfide, PVDF-polyvinylidene fluoride, PPSU-polyphenylsulfone, PEEK- polyether ether ketone, PSU-polysulfone, PFA-perfluoroalkoxyalkanes, PTFE-polytetrafluoroethylene, PCTFE- polychloro trifluoroethylene, PI- polyimide, PAI- polyamide-imide, PBI-polybenzimidazole.

dielectric constant, skin depth, and dielectric loss tangent were measured as output parameters. The experiments have shown that the dielectric constant is a useful factor for the detection of various plastic types in dry and wet samples. Absorption factor and dielectric loss tangent are found useful in the detection of plastics in dry samples. The detection technique is quick and accurate, and only a minute sample quantity is required. We expect that more electrical characteristics can be employed in plastic detection and identification using different cavity types and other existing microwave frequencies. As more types of exotic polymers are being developed and used for high performance and industrial applications, their detection in the environmental compartments needs to be quick and accurate to devise strategies for protecting human and ecological health. This study shows that alternative in-vitro methods for detecting hazardous plastic pollutants in environmental and biological samples can be developed based on microwave properties of various polymers. Further, the non-destructive method described in this paper can pave the way for developing different methods utilizing microwave and electrical properties that are hitherto undescribed in terms of environmental plastic detection methods.

CRediT authorship contribution statement

Renjith VishnuRadhan: Conceptualization, Formal analysis, Data curation, Investigation, Methodology, Writing – original draft. **Anil Lonappan:** Formal analysis, Writing – review & editing. **T.I. Eldho:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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