Environmental Impact of Phenolic Compounds: Advanced Detection using Active Inertial Electromagnetic Sensor

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Abstract:- Phenolic compounds are an important class of organic pollutants that are of considerable environmental concern. Compounds such as phenol and its derivatives are widespread pollutants in industrial effluents, mainly from oil-producing facilities, oil refineries, and agro-industrial processes, e.g., the extraction of olive oil. Furthermore, phenolic compounds are widely found in various food products and play an important role in some antioxidant properties and potential toxic effects related to their concentration and origin. Given their high toxicity, persistence, and potential for bioaccumulation, phenolic compounds have serious impacts on aquatic ecosystems, human health, and food safety. Thus, the rapid, sensitive, and low-background detection of them, with minimal preparation of the samples, would be highly beneficial for environmental monitoring, pollution management, and food quality testing. Here, we present the application of an Active Inertial Electromagnetic Sensor for the investigation of select phenolic compounds. This novel sensing technology provides real-time monitoring, high sensitivity, and the potential for on-site detection, creating opportunities to eliminate the need for time-consuming laboratory tests.

Key-Words: - phenolic compounds, electromagnetic signals, frequency, active inertial sensor, detection.

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1 Introduction

Phenolic compounds are a large class of organic compounds consisting of a hydroxyl group (-OH) attached to an aromatic hydrocarbon chain. They can be found in plants but are also widely produced in industries. Phenolic pollutants are generated by various sectors, including oil refining, petrochemical industries, pharmaceutical manufacturing, paper mills, textile factories, and agro-industrial activities such as olive oil and wine production. Because of their water solubility and stability against degradation, these substances often pollute lakes, soil, and air, which can pose a serious threat to ecosystems and human health, [1], [2], [3].

Phenolic compounds released into the environment can have devastating ecological effects. They are highly toxic to aquatic organisms by inhibiting enzymatic activity in microbes, fish, and amphibians, also disrupting metabolic and reproductive processes. Elevated levels can also deplete dissolved oxygen in the water, causing algal blooms and hypoxia that can be harmful to aquatic communities. Phenolic pollution in soil changes microbiome composition and affects important biogeochemical cycles, leading to soils with less fertility and also inhibition of plant growth. Furthermore, the volatilization of these compounds poses a significant air pollution risk, and their long-lasting presence makes remediation efforts particularly complex, [4], [5].

Currently, phenolic pollutants are very difficult to detect and remove. Conventional remediation processes, including chemical oxidation, adsorption, and biological degradation, are usually high-energy, complex processes, and potentially carry risks of secondary pollution. Likewise, traditional detection methods such as chromatography and spectrophotometry demand thorough sample preparation and laboratory analysis, making them impractical for real-time environmental monitoring. Therefore, rapid on-site detection methods are needed to provide better pollution management and reduce damage to the environment, [6], [7], [8].

One of the potential approaches to these problems is the Active Inertial Electromagnetic Sensor (AIES) for the real-time monitoring of phenolic compounds in wastewater, soil, and industrial effluent. This cutting-edge technology provides a non-invasive, simple, and affordable detection, minimizing the need for complicated laboratory testing. The implementation of AIES for environmental monitoring will help industries strengthen pollution control measures, minimize ecological threats, and advance green practices in industrial processes, [9], [10], [11], [12].

The contamination of phenolic compounds is an ongoing and widespread pollution problem in numerous places in the world; therefore, novel detection and remediation techniques should be developed and continually improved. Technologies such as AIES can greatly enhance both monitoring and compliance with production regulations to facilitate a transformation to cleaner production. By dealing with phenolic contamination, this sensor will help protect ecosystems, public health, and the long-term sustainability of our environment.

2 Materials and Apparatus

The experiment employs an innovative inertial system fashioned specifically for circular motion, intended to ensure the precision of material detection via the interactions of the electromagnetic signals. The system comprises four main components, including an electronic control unit, a telescopic antenna, a perpendicular axis, and a rotating base.

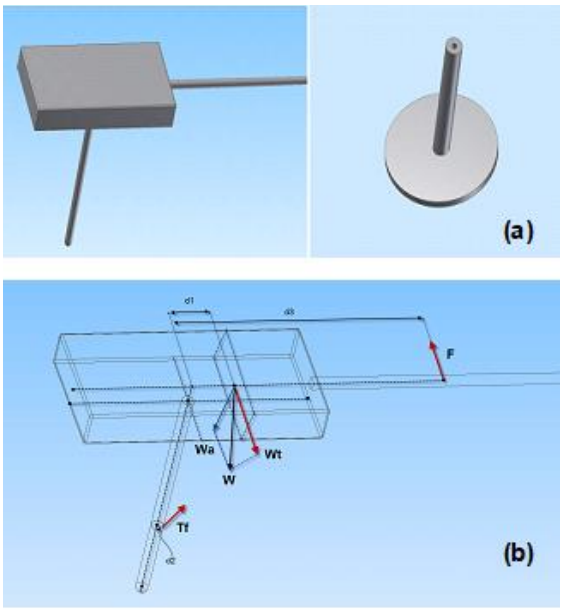

Fig. 1 (a): The inertia system consists of 2 pieces: Piece 1 is the Electronics box with the antenna attached to it, and the perpendicular axial fixed underneath the generator box. Piece 2 is the cylindrical base that can hold the generator and antenna. (b) The forces that are exerted on the antenna,
Source: [9]

As shown in Figure 1 and Figure 2, there are two main subsystems in the electronic control unit. The first subsystem is a signal-generating system,

which generates electromagnetic signals, while the second one is a force detection circuit, which detects external forces applied to the system. These signals are emitted via an external telescopic antenna, which comes bundled with the unit, and are used to interact with various substances. One component is the generator box, the other is the vertical axle that serves as the rotation axis of the system. The rotating base supports the entire system and permits free rotation around the axis of the pole, enabling stable rotational motion.

The system is divided into two components. The first includes the electronics box, antenna, and axial, and the second is a cylindrical base supporting the setup. When oriented away from vertical, the system will settle at its minimum energy configuration. When set in motion, it oscillates. Torque is generated because the weight of the first section induces damped oscillations around the axis. Forces acting on this motion are the weight component in the direction of motion and the friction resistance encountered in the system. These forces that are going to affect the angular velocity of the system during the run time can be shown in Figure 1.

Then, the total torque is calculated by the following equation:

$$\tau_{tot}(t) = d_1 \text{ x } W_t(t) - d_2 \text{ x } T_f(t) - d_3 \text{ x } F_t \text{ ,}$$

[9]

The signal generator applies an electromagnetic signal to the antenna. Based on the types of materials, different types of signals can be selected. As the antenna becomes aligned with a material, it exerts a further opposing force upon the movement of the system. The signal generation process is controlled by a microprocessor unit (MCU1) that receives settings input from a keyboard and display interface. The system can output signals with frequencies from 1 Hz to 100 kHz and has adjustable amplitude in the range of 1 V to 30 V peak-to-peak. It is powered by a 3.3V lithium battery (2700 mAh), which lasts up to 10 hours. In the next section describing signal generation, MCU1 provides the target material and instructs the Direct Digital Synthesis (DDS) unit on which signal must be created and passed through the antenna after amplification. Users can also adjust the amplitude of the signal as necessary.

Gray code (reflected binary code) is used for accurate monitoring of angular movement, effectively improving the accuracy of detected angles and enabling precise tracking of rotational changes. A wireless communication module also transmits angles to a desktop computer for real-time visualization.

While the sensor is rotating, the Gray disk detects the angle of the sensor´s bearing at a certain moment. If at this certain angle, deceleration is recorded, this indicates the existence of the substance we study.

This setup provides a reliable means of detecting materials based on their ability to modulate electromagnetic signal interactions, or the absence thereof, and the effect on the oscillatory behaviors of the inertial system, [9].

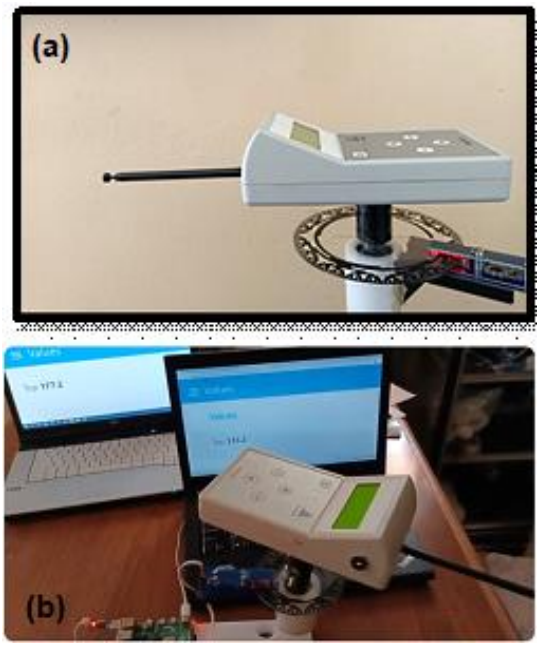

Fig. 2(a): Inertia system sensor, with Gray code disk and data transmission to a computer. It rotates in a circular movement around a vertical shaft. The sensor emits ultra-low (ULF) and very low frequencies (VLF) (3 Hz–30 kHz), Source: [12] (b). The setup shows the sensor, the Raspberry Pi, and the computer connected to them
Source: created by the authors

Concluding the description of the sensor, the following provides a brief overview of the substances that will be utilized in the experimental procedure.

The substances to be studied belong to the category of phenolic compounds and are as follows: phenol, benzoic acid, 4-hydroxybenzoic acid, and methyl 4-hydroxybenzoate.

2.1 Phenol

Phenol, or carbolic acid, is an aromatic organic compound with the formula. $\boldsymbol{C_6H_5OH}$, which consists of a hydroxyl group (−OH) bound to a carbon atom, which is part of an aromatic ring. At

room temperature, it is an odorless, colorless to white solid, but may appear slightly brown from oxidation. Phenol is an industrially relevant chemical used to produce plastics, resins, synthetic fibers, and bisphenol A for polycarbonate plastics and epoxy resins, [13], [14].

Phenol (Figure 3) naturally occurs in small amounts in certain plants and as a by-product of organic material combustion. It is poisonous and can irritate the skin, eyes, and lungs. Prolonged exposure can potentially lead to damage to internal organs, and it is classified as a carcinogen. Phenol is released from industrial processes into the environment, polluting water, soil, and air. It is chemically stable, persistent, and can bio-accumulate in aquatic organisms, posing a threat to ecosystems. The presence of phenol in contaminated sources is a severe environmental hazard that threatens ecosystem health and living organisms. Therefore, its detection is crucial for both environmental and human health, [15], [16].

Fig. 3: Crystalline form of Phenol
Source: created by the authors

2.2 Benzoic Acid

Benzoic acid is a monobasic aromatic carboxylic acid with excellent antifungal and antibacterial properties, and its ability to exist in an acidic environment. It contains a -COOH (carboxyl) group attached to a benzene ring that provides acidity and the capacity to bind diverse pharmacological targets. Found in certain mushrooms, some fruits (excluding berries), and a few spices, including cinnamon, benzoic acid is a popular preservative. It prevents the growth of bacteria and fungi in acidic food, such as soft drinks, jams, and juices, and is the common preservative E210, found in many products, [17], [18], [19].

An antiseptic and disinfectant, benzoic acid is used in medicine as the basis for the creation of several pharmaceutical products. It used to be found in creams, shampoos, and other formulations to inhibit microbial contamination. It has also attracted much scientific interest as an antioxidant that protects cells from damage caused by free radicals, which are unstable molecules that can affect different cellular components. While it has so many beneficial uses, various regulatory bodies have limited its use to prevent potential negative health effects with overdoses, [20], [21].

Commercial packaging of Benzoic acid that was used for the experiment can be seen in Figure 4.

Fig. 4: Commercial packaging of Benzoic acid that was used for the experiment. The quantity and the purity of the substance are shown
Source: created by the authors

2.3 4-Hydroxybenzoic Acid

It is an aromatic carboxylic acid, a kind of benzoic acid. It has a hydroxyl (-OH) group on the para (4th) position on the benzene ring. This compound is present in several plants and fruits and contributes to the production of parabens, common preservatives used in cosmetics and food products because of their capacity to inhibit microbial growth and increase shelf life. In addition to its preservative effect, 4-hydroxybenzoic acid also has antioxidant activity, protecting cells against damage from free radicals. The most common application is in the production of parabens for the food and cosmetic industries, [22].

Pharmacological investigations have also demonstrated its anti-inflammatory and antimicrobial effects, indicating potential therapeutic benefits. Found naturally in foods like carrots, onions, and strawberries, it must be used with care because too much can cause allergic reactions in some people. Its health effects and methods to enhance its antioxidant and

antimicrobial properties are areas of ongoing research, [23], [24], [25].

Commercial packaging of 4-Hydroxybenzoic acid that was used for the experiment is shown in Figure 5.

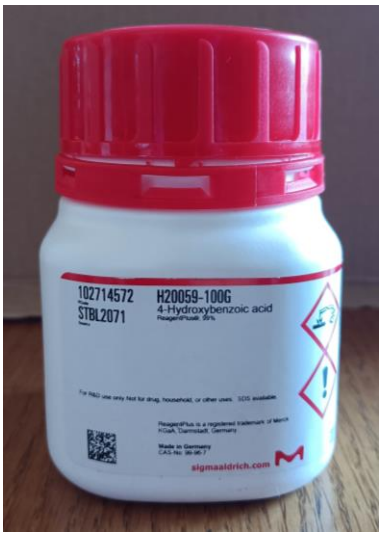

Fig. 5: Commercial packaging of 4-Hydroxybenzoic acid that was used for the experiment. The quantity and the purity of the substance are shown
Source: created by the authors

2.4 Methyl 4-hydroxybenzoate

Methyl 4-hydroxybenzoate (methylparaben) is a preservative belonging to the benzoic acid family. Its chemical design contains a benzene band with a hydroxyl band (-OH) in the para (4th) placement and a methoxy band (-$COOCH_3$), making it soluble in herbal solvents. It is an antifungal and antibacterial compound that has made it widely used in cosmetics, pharmaceuticals, and food products, [26], [27]. It is referred to as additive E218 in the food industry and is present in jams, sauces, and soft drinks, [28]. It is also often incorporated into cosmetics, including creams, shampoos, and makeup, as a preservative to inhibit microbial contamination and prolong shelf life. This compound is stable over wide pH ranges, which increases the scope of formulations used. Although in low concentrations, it is generally considered to be of low risk, there are worries that it may act as an endocrine disruptor or cause allergic reactions in sensitive individuals. This is why regulatory bodies have imposed certain limitations on how it can be used, which is vital to keep it as a safe ingredient for consumers, [29], [30].

The quantity and the purity of Methyl 4-hydroxybenzoate (methylparaben) that was used in the experiment can be seen in Figure 6.

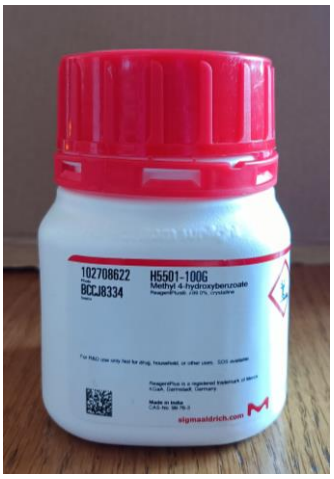

Fig. 6: Commercial packaging of Methyl 4-hydroxybenzoate that was used for the experiment. The quantity and the purity of the substance are shown
Source: created by the authors

Table 1 (Appendix) summarizes the four introduced phenolic acids, together with their chemical formulas and two-dimensional (2D) and three-dimensional (3D) molecular models. These visualizations demonstrate the structural characteristics within each compound as they describe specific locations of atoms and functional groups, which elicit their chemical and biological behaviors.

3 Experimental Procedure

The following experimental procedure describes an accurate way of finding the resonant frequencies of the aforementioned substances.

In the absence of an external magnetic field, the number of nuclei in the spin-up state is approximately equal to that in the spin-down state (m = -1/2), with a slight numerical excess in the spin-up (m = +1/2) state. However, when the nucleus is placed in a magnetic field, this equilibrium changes. The magnetic moment of the nuclei interacts with the externally applied magnetic field, and thus, the two spin states no longer have the same energy. The energy difference between the two states is calculated by the equation:

$$\boldsymbol{\Delta E = \gamma \hbar B_0}$$

where γ is the gyromagnetic ratio, ħ is the reduced Planck constant, and B_0 is the magnetic field strength, [31], [32].

The frequency corresponding to this energy is known as the Larmor frequency, [33], [34], [35], [36], [37]. Since the Larmor frequency depends on

the magnetic field at the nucleus, the nuclear shielding effect reduces the intensity of the nuclear magnetic field, resulting in a shift in the Larmor frequency, known as chemical shift, and is calculated by the equation, [38], [39], [40]:

$$\boldsymbol{\delta = \frac{(f_{substance} - f_{reference})}{f_{reference}} \text{ x } 10^6}$$

and is measured in ppm, which is independent of the applied magnetic field B.

By following this procedure step by step, we aim to identify the frequencies at which a material resonates when irradiated with electromagnetic signals.

Step 1: Initial Frequency Scan
To begin, initially, the substance under study is placed in a prearranged position, opposite the AIES. When the material is in place, we activate the AIES and program the settings so that it scans a range of frequencies. It is necessary to set the frequency where the scanning will begin (lowest frequency) and the frequency where the scanning will end (highest frequency).

Then, we select a mode where the emitted frequency increases by 10 Hz every 5 seconds. The sensor is set in motion, and we observe the motion of the sensor. If a deceleration takes place, this could mean that the specific frequency that is emitted at a certain point in time could be a resonant frequency of this substance. We repeat the same procedure for the whole frequency range, ensuring that we have recorded all the possible resonant frequencies for this substance.

Step 2: Verification of Potential Frequencies
When we record the first set of potential resonant frequencies, we proceed with their verification. The substance remains at the same position as in Step 1, to make sure that there is consistency in the experimental procedure. We switch AIES to a different mode, where the emitted signal (frequency) remains the same over time, instead of being gradually increased as in the previous step. Starting with the first frequency that was recorded in Step 1, we set AIES to emit this frequency while the sensor is moving. We then observe the motion of the sensor. If the sensor decelerates, we record this frequency as the resonance frequency. If no deceleration is observed, the frequency is discarded. This procedure is repeated for every frequency that was recorded in Step 1. When Step 2 finishes, we have a refined list of possible resonant frequencies.

Step 3: Repositioning the Material
Next, the substance is moved to a new position, ensuring that it remains at the same distance from the sensor as it was in the previous steps. This step helps us confirm that the frequencies we recorded previously are indeed the resonant frequencies for this substance, and the sensor is not affected by altered spatial conditions. While the substance is in the new position, we repeat the same process that was described in Step 2. The frequencies we use are the frequencies we recorded in the final list of Step 2. Once again, AIES is set to emit certain frequencies, and we monitor for deceleration in the movement of the sensor. After completing this step, we record the frequencies that decelerate the sensor, while all the others are discarded.

Step 4: Re-verification of Frequencies
Step 4 repeats the procedure of Step 2, but this time we use only the frequencies that survived the procedure in Step 3. The material is placed in a new position again, and AIES is set to emit the remaining frequencies in turn. Once again, we observe the motion of the AIES. When deceleration is observed, we record the specific frequency. This extra verification allows us to make the final list of the resonant frequencies of the substance.

This procedure (Steps 1 to 4) is repeated for all the substances that are going to be studied in this experimental procedure. By following the procedure, we make sure that the resonant frequencies of each substance are accurately identified.

4 Results and Discussion

Table 2 (Appendix) presents the resonant frequencies of each of the substances that were studied. The frequency range that we studied was 1000 Hz to 2000 Hz. By analyzing the data, it is found that the majority of the recorded frequencies of these substances are common. This phenomenon suggests that there are common molecular fragments and functional groups in these substances, which play a significant role in their vibrational behavior. More specifically, according to the phenolic compounds that were studied -that is, phenol, benzoic acid, 4-hydroxybenzoic acid, and methyl 4-hydroxybenzoate- exhibit common resonant frequencies at 1060 Hz, 1440 Hz, 1560 Hz, 1750 Hz, and 1940 Hz. Therefore, it becomes evident that substances that can be detected by the same frequencies have similar structural characteristics.

More specifically, these compounds contain functional groups such as the phenolic (-OH) and

carboxylic (-COOH) groups, which take part in specific vibrations. For instance, the vibrations related to O-H stretching in the phenolic group could contribute to the detected resonant frequencies. The presence of common resonant frequencies is very important, as it allows the simultaneous detection of more than one phenolic compound through the AIES. Additionally, the identification of the common resonant frequencies provides useful information about the chemical composition and possible biological characteristics. Analyzing the structural similarities and vibrational characteristics of these compounds, researchers will be able to better assess the role of these compounds, or similar, in various biological systems and could improve future methods of detecting contaminated waters, soils, etc., due to phenolic compounds.

Although the aforementioned substances have some identical frequencies, there are some others that are unique to each substance. As can be seen in Table 2 (Appendix), frequency 1260 Hz is unique for methyl 4-hydroxybenzoate, while frequencies 1640 Hz and 1840 Hz are unique for benzoic acid. This is expected because the previous substances have slight differences in their molecules, so it is expected to have some resonant frequencies that differ from those of other substances.

5 Conclusion

AIES made it possible to identify accurately the resonant frequencies of some phenolic compounds, which are some of the most common pollutants in ecosystems. We were able to detect these compounds by using a non-invasive electromagnetic sensor that exploits the characteristic resonant frequencies of phenolic compounds.

The ability of the sensor to identify chemical signals of phenolic compounds allows monitoring of the environmental quality, detecting the presence of these compounds in areas where there is a possibility of contamination. In addition, this sensor can be used for monitoring environmental conditions in places where the presence of phenolic compounds is undesirable or even dangerous, such as water, soil, or the atmosphere.

This sensor could be very useful in the future as it has many applications. It could detect dangerous substances in the early stages of contamination of soil, water, or air. It could also be used as a method of constantly monitoring and detecting the phenolic compounds. This is very important because these compounds are toxic to biodiversity and human health, [41].

Specifically, AIES could be used for fast tracking, on-site testing, and mapping of sources of contamination because of the extraction of phenolic substances in multiple environments. In olive mill wastewater (OMW), there are high concentrations of toxic polyphenolic compounds that are harmful to aquatic ecosystems. In this case, the sensor allows the immediate detection of these compounds before or during the wastewater treatment in order to proceed with targeted sampling and Liquid Chromatography–Mass Spectrometry (LC-MS) confirmation and containment measures to be applied.

In pulp and paper industries, it could alert to the sudden existence of phenolic compounds in the waste products, preventing pollution of streams and rivers.

In landfills, its use for leachate monitoring makes it easier to organize the sampling points and to map the spreading of pollutants such as phenols, chlorophenols, etc.

It can also be used for screening at wood-processing sites and brownfield areas contaminated with creosote, detecting phenolic preservatives, as well as for monitoring surface waters near pharmaceutical or chemical facilities, where the presence of phenolic compounds in products or byproducts could be released in the environment.

Thus, the development and use of this sensor could play a critical role in the prevention of environmental disasters and could also reinforce the efforts of keeping the environment safe and healthy.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed and edited the content as needed and verifies that none utilised artificial intelligence (AI) tools were used. The authors take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Erietta Vasilaki organized and executed the experiments, carried out the data analysis, wrote and revised the original draft.
- Antonia Psaroudaki revised the final draft.
- Diamanto Lazari provided the resources.
- Evaggelia Drakaki carried out the data analysis.
- Chrysi Logaki Investigation and research
- Emmanouel Antonidakis supervised the experiments, provided the resources, and revised the final draft.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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APPENDIX

Table 1. Chemical, as well as 2D and 3D forms of the molecular structures of the four phenolic compounds used

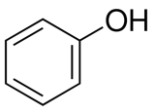
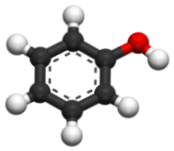
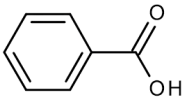
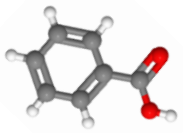
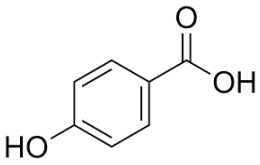
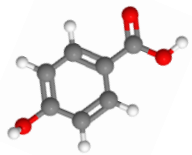
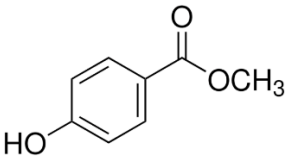
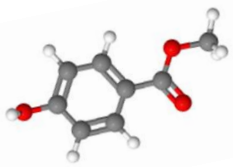
Name	Chemical Formula	Molecular Formula	3D Simulation
phenol	C_6H_6O		
benzoic acid	$C_7H_6O_2$		
4-hydroxybenzoic acid	$C_7H_6O_3$		
methyl 4-hydroxybenzoate	$C_8H_8O_3$		

Table 2. The table below provides the resonance frequencies for each of the five phenolic compounds utilized in the experimental procedure. It also includes the shared frequencies at which these compounds can be detected. It can be seen in the previous Table that phenol, benzoic acid, methyl 4-hydroxybenzoate, and 4-hydroxybenzoic acid share the frequencies 1060 Hz, 1440 Hz, 1750 Hz, and 1940 Hz. Frequency 1260 Hz is unique for methyl 4-hydroxybenzoate, while frequencies 1640 Hz and 1840 Hz are unique for benzoic acid.

resonant frequencies (Hz)	phenol	benzoic acid	methyl 4-hydroxybenzoate	4-hydroxybenzoic acid
1060	✓	✓	✓	✓
1260			✓	
1310	✓			
1440	✓	✓	✓	✓
1560	✓	✓	✓	
1640		✓		
1750	✓	✓	✓	✓
1840		✓		
1940	✓	✓	✓	✓