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Article

Integration of iron oxide nanoparticles into high-density polyethylene for sustainable cup coatings

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SUMMARY

Microplastics persist across a wide range of ecosystems, including oceans, remote islands, and polar regions. They pose serious health and environmental risks: their toxicity and accumulation in biological systems are linked to inflammation and blood clotting in humans, while in ecosystems they disrupt food webs, reduce organismal fitness, and contribute to soil ecotoxicity. In this study, we hypothesized that incorporating magnetic iron (II) oxide nanoparticles into disposable cup linings could produce a waterproof magnetic polymer liner for paper cups. This integration may improve the recovery of plastic components from composite waste through magnetic recycling and reduce the risk of microplastic contamination in the environment. Iron (II) oxide is a magnetic compound that, if incorporated correctly, would not interfere with high-density polyethylene used in disposable paper cups, allowing it to maintain hydrophobic properties without disrupting structural integrity. For this study, iron (II) oxide nanoparticles were synthesized using iron (II) sulfate and iron (III) chloride, and characterized by energy dispersive X-ray spectroscopy and dynamic light scattering to confirm composition and size. Further, the liner's magnetic properties were characterized through a magnetic field test. Our results demonstrated that the iron (II) oxide nanoparticles exhibited strong magnetic responsiveness and successfully bonded with the plastic layer, enhancing its manipulability. These findings suggest that iron (II) oxide nanoparticles could serve as a potential method for enhancing the recyclability of disposable cups while mitigating microplastic pollution, offering a potential possibility for broader industrial application in sustainable material development.

INTRODUCTION

Microplastic pollution has increased exponentially over the past 50 years and is a critical environmental and public health issue, with pervasive effects on ecosystems and human health (1). Microplastics, defined as particles between 0.1–5000 µm, have been documented disrupting nutrient cycles in oceans, freshwater systems, soil, and even polar ice (1). Microplastics can also easily enter the human body through direct or indirect ingestion, with the average person consuming five grams of microplastics per week (2). Disposable cups, which are used by millions globally every day, are a significant source of this pollution, with 99.75% of 120 billion disposable coffee cups alone ending up in the trash (1,3). The plastic materials in these cups degrade into microplastics, which enter the environment and, upon ingestion, pose serious health risks, such as blood clotting (4).

Current strategies to address microplastic pollution have centered on reducing plastic consumption, expanding recycling capacity, and introducing biodegradable alternatives, yet each has significant limitations (5). Many so-called biodegradable plastics require controlled conditions of industrial composting facilities to fully degrade, conditions that are rarely met in everyday disposal (5). Recycling systems remain underdeveloped in much of the world; more than 8.3 billion metric tons of plastic have been produced since the 1950s, yet only about 9% has ever been recycled, and 79% has accumulated in landfills or in the natural environment (6). Inadequate infrastructure in low and middle-income countries further exacerbates this problem. For example, less than 15% of plastic waste is collected for recycling in Asia, despite Asia being the world's largest producer and consumer of plastics (7). Moreover, efforts to curb consumer demand have also faced resistance, as the convenience and low cost of single-use plastics continue to drive commercial use (6).

Iron oxide nanoparticles (IONPs) can improve recycling rates, especially for multi-composite objects such as paper cups. IONPs are nanoscale forms of iron oxides. They are notable because of their superparamagnetic behavior at small sizes, which allows them to be strongly influenced by external magnetic fields without retaining permanent magnetization (8). This makes them attractive for applications where controllable magnetism is required (9). Moreover, the magnetic properties of IONPs can potentially make plastic products easier to sort and recycle. In conventional recycling processes, separating plastics from other materials is often labor-intensive and inefficient. However, with IONP-coated plastics, magnetic sorting technology can be used to quickly and accurately separate these items from general waste. This could improve the efficiency of recycling facilities and may increase the likelihood that plastic products are properly recycled rather than ending up in landfills or the ocean. IONPs have already been adopted in medicine, such as in U.S. Food and Drug Administration (FDA)-approved magnetic resonance imaging (MRI) contrast agents and treatments for iron deficiency, and in environmental remediation, where they are used to magnetically separate heavy metals, dyes, and even microplastics from water systems (10, 11).

The benefits of IONPs lie in both their magnetic responsiveness and their ability to modify material properties when incorporated into polymers (9). Studies show that nanoparticles can strengthen polymer matrices, improving resistance to cracking and fragmentation, which are processes that contribute to microplastic formation (12). At the same time, nanoparticles still pose potential risks. Depending on size, coating, and concentration, IONPs can generate oxidative stress and inflammatory responses in biological systems if released in high amounts (13). For this reason, applications in consumer products require that IONPs remain well-bound within a polymer matrix to prevent leaching (14).

Based on these advantages, we hypothesized that IONPs could serve as a stable, magnetic addition to disposable cup coatings while retaining the high-density polyethylene (HDPE) layer's hydrophobicity, thereby potentially enabling magnetic recyclability and separation of the cup's paper–plastic composite layers. To test this, we synthesized IONPs through precipitation methods using iron (II) sulfate and iron (III) chloride. Following this, we characterized IONP size and magnetism responsiveness through dynamic light scattering (DLS) and magnetic field tests, respectively. The results suggest that IONPs are suitable for incorporation into HDPE to separate disposable paper cups for magnetic recycling.

RESULTS

The first step of this project was to make IONPs for their incorporation into polymers that could be used to line the inside of cups. We used 2M iron (II) sulfate ($FeSO_4$), 1M iron (III) chloride ($FeCl_3$), and 0.10M sodium hydroxide (NaOH) solutions and followed precipitation and settling procedures to produce IONPs (15). Subsequently, heating and grinding enhanced the crystallinity and the dispersibility of the synthesized IONPs (**Figure 1**). Nanoparticles obtained directly from the co-precipitation process often retain residual surface water, exhibit irregular morphologies, and form loose agglomerates, all of which contribute to a broad particle size distribution (16). Heating assisted in driving off solvent residues and promoted the crystallization of iron oxide phases, thereby improving structural stability (**Figure 2A**) (16). Subsequent grinding disrupted larger aggregates, yielding a finer and more uniform powder (**Figure 2B**) (8, 16). The IONPs resulted in a fine powder mixture after heating and grinding (**Figure 1**). We then measured particle size using DLS, a technique that tracks how nanoparticles scatter light as they move randomly in suspension (17). Using DLS, the IONPs showed a hydrodynamic diameter of 185.7 ± 3.5 nm (average ± standard deviation (SD), n = 4), which is within the optimal nanoparticle size range of 1–200 nm. The spectra showed multiple peaks, with the larger peaks corresponding to clustered particles formed during synthesis, while the smaller peak reflected the main nanoparticle population (**Figure 2B**).

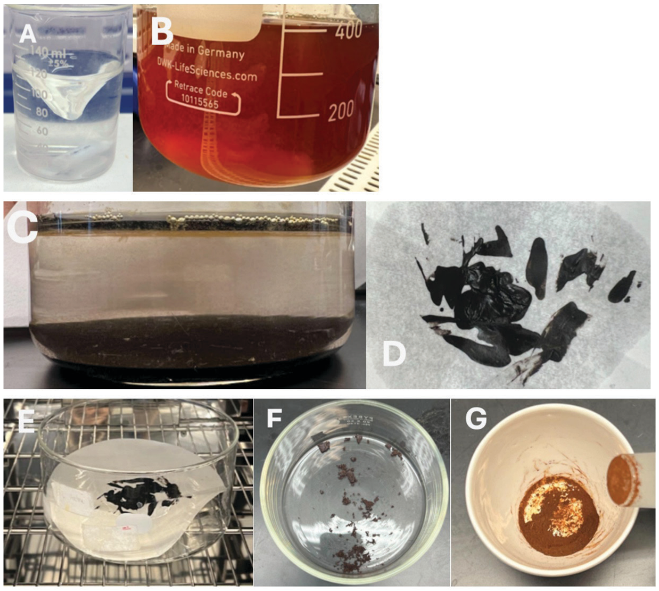

Figure 1: Iron oxide nanoparticle synthesis through a precipitation process. Representative photos were taken of (**A**) dissolved sodium hydroxide pellets, (**B**) iron (III) sulfate and iron (II) sulfate, (**C**) the iron (III) sulfate and iron (II) sulfate mixture with a sodium hydroxide solution left to settle for an hour, (**D**) iron oxide nanoparticle solution as an ink-like consistency, (**E**) iron oxide nanoparticles heated at 200°C, (**F**) iron oxide nanoparticles collected after heating, and (**G**) iron oxide nanoparticles after grinding into a fine powder.

Next, we incorporated IONPs into HDPE. HDPE was chosen as the polymer matrix because it is the material most used to line disposable coffee cups (18). Its hydrophobicity and durability make it effective for holding hot liquids, and using it in this study ensures that the results are directly relevant to commercial products (3). When the HDPE was heated and melted into a viscous state, the IONPs were uniformly distributed within the plastic, creating a well-integrated composite material (**Figure 3**). The final resulting HDPE-IONP composite had a total mass of 0.301 g (with 0.028 g of IONPs and 0.273 g of HDPE), and possessed magnetic properties from the IONPs. This demonstrates successful IONP integration in HDPE as shown in tests where a standard cylindrical magnetic rod (measuring 2 cm in diameter and 10 cm in length with a magnetic strength of 15,000 gauss) magnetically attracted the HDPE-IONP coated layer from a distance of ±2.5 cm (**Figure 4C**). Moreover, we used energy-dispersive X-ray spectroscopy (EDS) to analyze the elemental composition of the pure synthesized nanoparticles by detecting the characteristic X-rays emitted when the sample was exposed to an electron beam. This technique is particularly valuable in nanoparticle research because it provides rapid, site-specific information about elemental presence and relative abundance (17). In this study, EDS was selected to verify the successful incorporation of iron and oxygen into the nanoparticles, and the results confirmed the presence of the expected elements iron (Fe) and oxygen (O) within the IONPs (**Figure 5**). Although EDS could not determine the specific type of iron oxide, it is highly likely that the nanoparticles were iron (II) oxide, given that the experimental protocol for synthesizing this form of iron oxide was meticulously followed (15).

The IONP-HDPE composite, initially formed into a ball-like shape, was easily pressed into a thin sheet using a rolling pin and further retained its magnetic properties. Although the IONP small size causes them to be manipulated easily, their size also means that a relatively large quantity is required to impart significant magnetic properties. For instance, to achieve detectable magnetism in a sample of HDPE applied to a disposable cup, a ratio of 0.056 g IONPs to 0.546 g HDPE was necessary (**Figure 4C**).

Hydrophobicity is a critical property for disposable cup linings because it prevents liquid absorption and helps the material maintain structural integrity when in contact with hot or cold beverages. To maintain the waterproof functionality

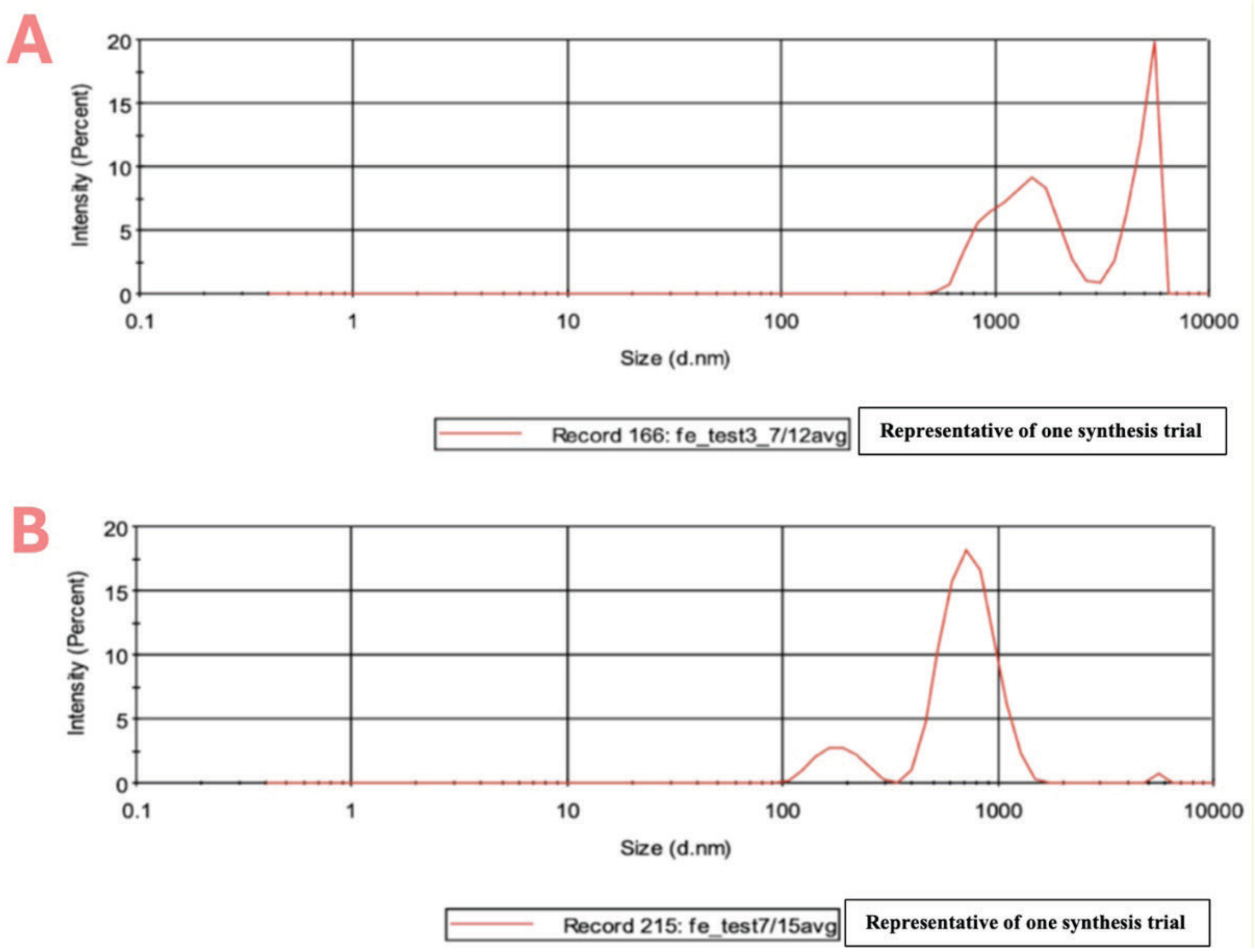

Figure 2: Dynamic light scattering measurements of iron oxide nanoparticles showing their nanometer dimensions from a single batch. (**A**) Dynamic light scattering scan result of iron oxide nanoparticles after settling, before heating and grinding. (**B**) Dynamic light scattering scan result of iron oxide nanoparticles after heating and grinding. The y-axis shows "Intensity (Percent)", which is the share of scattered light coming from particles of a certain size. Larger particles show greater intensity because they scatter more light.

of disposable cups, the HDPE and IONP layer needed to exhibit comparable waterproof qualities to the original plastic layer. The incorporation of IONPs did not change the hydrophobic behavior of HDPE. To verify this, a contact angle experiment was conducted, which measures the angle formed between a liquid droplet and the solid's surface as an indicator of surface wettability and hydrophobicity. The results showed that the IONP-infused HDPE surface had similar water droplet spreading to a standard commercial cup lining (**Figures 6B, C**). Thus, observations suggest that the addition of IONPs did not diminish the water-repellent behavior of HDPE, an important property for disposable drinking cups, but did provide magnetic responsiveness for potential magnetic waste separation.

DISCUSSION

This study tested the hypothesis that incorporating IONPs into HDPE cup linings could produce a magnetic HDPE polymer liner for paper cups that retains waterproof properties and is suitable for magnetic recycling. The results support this hypothesis; IONPs retained magnetic responsiveness when integrated into HDPE, dispersed uniformly in the polymer matrix, and did not visibly alter hydrophobicity under testing. The findings from this study demonstrated that IONPs may potentially enhance recyclability while maintaining the waterproof properties of the material. However, a more rigorous contact angle analysis would be needed to determine whether the composite's hydrophobicity is comparable to that of commercial cup coatings. Further, although EDS could not identify the precise oxidation state which would require further testing, the synthesis protocol was designed to yield Fe_2O_3, which was chosen for its stability, nanoscale magnetic responsiveness, and relatively safe toxicity profile (19, 20).

We demonstrated here that IONPs can be incorporated into HDPE without loss of their magnetic properties. To evaluate the magnetic responsiveness of IONPs when integrated with HDPE, the positive control consists of IONPs alone, whose iron content confers inherent magnetism. The negative control is neat HDPE, which is non-magnetic; comparing it with the HDPE–IONP composite reveals whether the composite gained magnetic properties. This integration process not only preserved the magnetic responsiveness of

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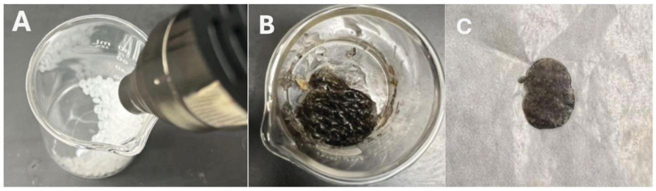

Figure 3: High-density polyethylene (HDPE) synthesis with compressed iron oxide nanoparticles (IONPs). Representative photos were taken of (**A**) HDPE pellets melted using a heat gun, (**B**) HDPE combined with IONPs, and (**C**) a flattened and cooled HDPE and IONP layer.

the IONPs but also allowed the HDPE mixture to be easily shaped into a thin, uniform layer (**Figure 6A**). However, since no direct comparison was made with neat HDPE under the same conditions, it cannot be concretely concluded whether the addition of IONPs altered the manipulability or consistency of the plastic.

Consistent with this observation, we found that the composite could be pressed into thin, uniform layers, suggesting that the material remains workable for use in cup linings. Although this does not establish its suitability for broader manufacturing applications, related research on nanoparticle-polymer composites has shown improvements in material performance and recyclability, supporting the possibility of future development in this direction (12).

During synthesis, the yield of IONPs was relatively low, with only 1.150 g of nanoparticles obtained alongside 140 mL of waste solution. While this does not directly affect the study's findings, it has practical implications for scalability and efficient resource use. A lower yield means fewer nanoparticles are available to be incorporated into the polymer, which in turn reduces the overall magnetic responsiveness of the HDPE–IONP composite. This is because the strength of the observed magnetism is not only dependent on the intrinsic properties of the IONPs but also on the quantity of magnetic material present. When fewer nanoparticles are available, the composite requires a stronger external magnetic field to demonstrate detectable magnetic attraction.

In practical applications such as waste separation, industrial magnets with much higher field strengths than those used in this study could overcome this limitation (21). However, improving synthesis efficiency to produce larger yields would reduce reliance on high-powered magnets and make the process more resource efficient. Future work should therefore examine both synthesis optimization, to increase nanoparticle yield, and the influence of various magnet strengths, to improve recovery and sorting efficiency, as complementary strategies.

The stability of IONPs within the polyethylene matrix is an important factor for their safe use in consumer products. Once the material cools and is shaped into its desired thin layer, the IONPs become securely embedded within the polyethylene matrix. The only conditions likely to cause displacement are physical degradation of the polyethylene layer or exposure to temperatures high enough to melt the polymer (22). In the context of disposable cup use, this might occur if the cup is exposed to very hot liquids or placed in a microwave. However, typical cup components such as plastic, paper, and foam exhibit low thermal effusivity and conductivity, with reported conductivity values ranging from 0.05–0.34 W/m·K at 20–23°C, which is relatively low for effective heat transfer (23). Therefore, the likelihood of heat causing damage to the polyethylene layer is minimal, although this would require additional studies. Even if the plastic layers were compromised, the IONPs would remain bonded to the polyethylene, significantly reducing the chances of nanoparticle ingestion from disposable cups.

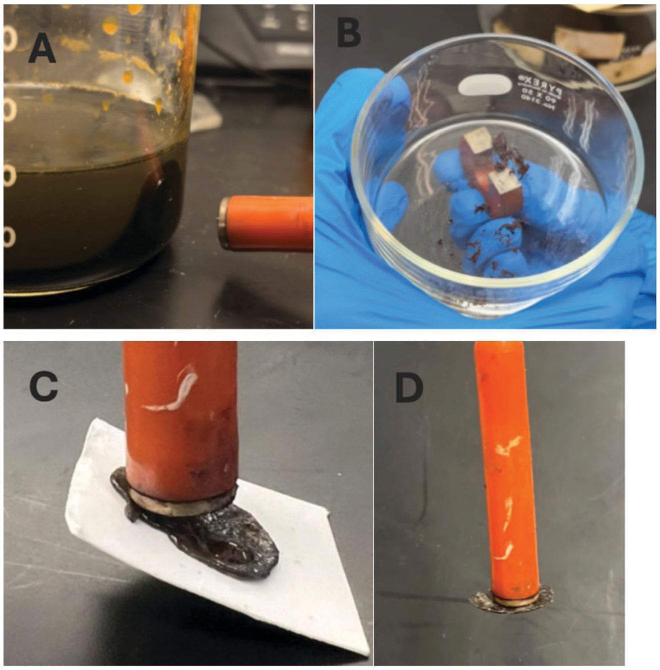

Figure 4: Iron oxide nanoparticles (IONPs) and high-density polyethylene (HDPE) composite's attraction to a magnet. A magnet (in orange) was used to test the magnetism of IONPs (**A**) in the solution, (**B**) after heating and a drying magnet was used to attract IONPs through glass, (**C**) magnet attracts the IONP-HDPE composite attached to a disposable cup's paper layer, and (**D**) magnet attracts the IONP-HDPE composite.

Further, if a consumer were to accidentally ingest IONPs, the IONPs would not pose a significant threat to the individual's health. The primary component of IONPs is iron, an essential element already present in the human diet (24). Iron supplements are widely used, and iron is known to support the production of hemoglobin, thereby enriching the circulatory system (25, 26). Further evidence of their safety profile is the approval of certain IONPs by the U.S. FDA for the specific treatment of chronic kidney disease and iron deficiency (27). Additionally, IONPs are used as contrast agents in MRI, demonstrating their biocompatibility in controlled medical environments (28). However, consuming extremely high doses of iron, typically over 20 mg, poses potential side effects such as constipation, nausea, and stomach discomfort; the amount of iron derived from IONPs in a single disposable cup, or even multiple cups, would be far below this threshold (26). Furthermore, for ingestion to occur, the HDPE layer would first need to be compromised, which is highly unlikely. Therefore, the risk of the IONP-HDPE layer in disposable cups posing any harm is minimal, although this

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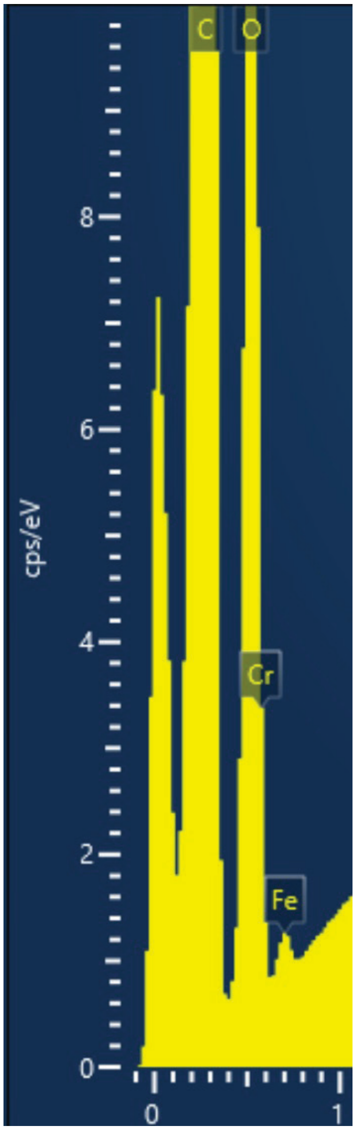

Figure 5: Energy dispersive spectrum (EDS) of iron oxide nanoparticles (IONPs) formulated in the study from a single trial. EDS was performed to identify the elements in IONP samples by analyzing X-rays emitted from the sample (n=4). C has a peak at about 0.3 KeV, O at 0.6 KeV, and Fe at 0.7, 6.4, and 7.1 KeV.

should be further evaluated before implementation.

The addition of magnetic properties through IONPs provides a practical benefit for sustainability and waste management by making the plastic linings of disposable cups magnetic, allowing for easier separation of these cups from other waste, especially in large-scale recycling operations. This magnetic feature enables sorting of plastics using magnetic fields commonly found in developed countries, which can aid the recycling process and ease the pressure on waste management systems (29). This approach supports efforts toward a circular economy by making it easier to recycle materials that would otherwise end up in landfills. The global production and use of disposable paper cups is estimated at around 500 billion units each year, the vast majority of which are discarded after a single use (30). Most of these cups end up in landfills or the natural environment, with less than 1% currently recycled due to the difficulty of separating the polyethylene lining from the paper (30). By integrating IONPs in plastic products to separate the disposable cup's HDPE layer from its paper composite, we address two major environmental challenges: microplastic pollution and inefficient recycling. Overall, incorporating IONPs into plastic products may promote environmental sustainability by both reducing the creation of microplastics and enhancing recycling efforts, contributing to a more circular economy where materials are reused rather than discarded.

MATERIALS AND METHODS

IONP Production

First, 10.647 g of iron (II) sulfate ($FeSO_4$) was weighed and dissolved in 35 mL of distilled water to make a 2M solution. This mixture was stirred using a magnetic stirrer for about five minutes until the $FeSO_4$ was completely dissolved. Similarly, 8.276 g of iron (III) chloride ($FeCl_3$) was weighed and dissolved in 51 mL of distilled water to prepare a 1M solution, which was also stirred until fully dissolved. The two iron solutions were then combined in a large beaker and thoroughly mixed using a magnetic stirrer (**Figure 2A, 2B**). All chemicals used were sourced from Sigma Aldrich.

Next, a 0.10 M NaOH solution was prepared, then gradually added to the combined iron solution while continuously stirring. The pH of the mixture was carefully monitored and adjusted by adding NaOH until it reached a pH of 12.9. This was done slowly to avoid rapid pH changes and potential side reactions. The addition of 80 mL NaOH caused the solution to darken and turn highly basic as tested by litmus paper, indicating the formation of iron oxide nanoparticles.

The mixture was allowed to settle for 1.5 hours, during which time the IONPs precipitated out of the solution. As the mixture settled, it separated into two layers: a clearer upper layer, and a darker bottom layer containing the precipitated nanoparticles (**Figure 1C**). The supernatant was carefully decanted or pipetted off to remove unreacted chemicals and by-products. The remaining iron oxide nanoparticles were filtered using filter paper, resulting in a pure, ink-like, dark, black product (**Figure 3D**).

Finally, the collected nanoparticles were transferred to a drying oven set to 200°C and dried for 1 hour. After drying, the nanoparticles were allowed to cool to room temperature and were then grinded using a mortar and pestle before being collected as a powder (**Figure 3G**). The mean final mass of the iron oxide nanoparticles was measured at 0.575 g per synthesis, averaged across four synthesis reactions.

DLS Analysis

DLS analysis was performed using a Malvern Zetasizer Nano ZS. For each trial, approximately 1 mg of nanoparticles was re-dispersed in distilled water, sonicated for 10 minutes to minimize agglomeration, and placed in a disposable cuvette for measurement at a 173° backscatter angle. Zetasizer software was used to process the data using the cumulant method to calculate hydrodynamic size distributions.

Fabrication of the HDPE-IONP Composite

A sample of 0.273 g HDPE pellets was melted using a

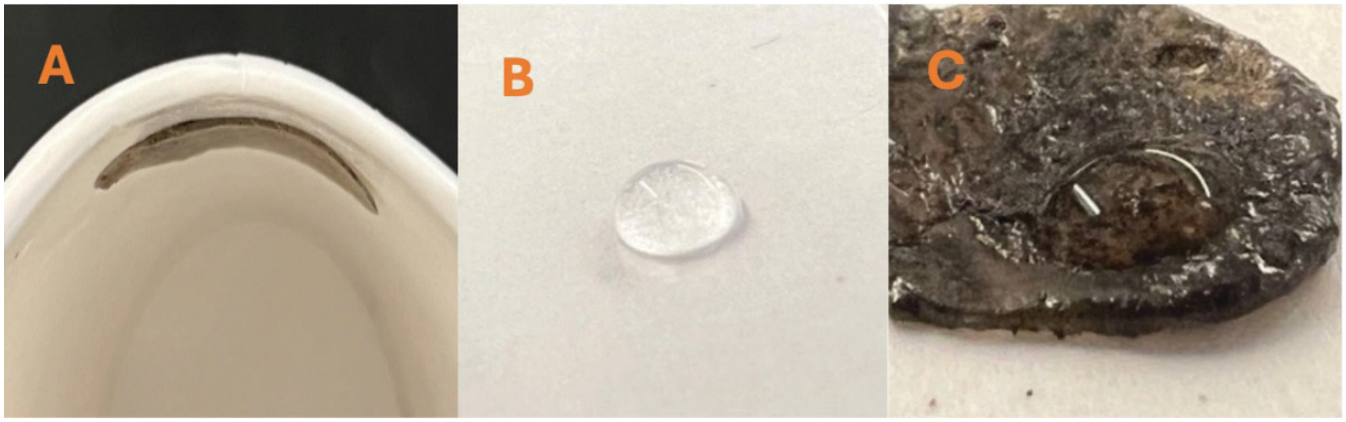

Figure 6: Hydrophobicity of high-density polyethylene (HDPE) and iron oxide nanoparticle (IONP) composites when coated on disposable cups. (**A**) Sectional prototype of a flattened high-density polyethylene and iron oxide nanoparticle layer on disposable cups. Contact angle test using distilled water on a (**B**) regular commercialized cup polyethylene layer vs. (**C**) a high-density polyethylene and iron oxide nanoparticle layer.

heat gun set to 300 degrees Celsius, positioned at a distance of 7 cm away from the pellets. The HDPE, initially in a solid state, began to melt within the first minute and reached a viscous state by the second minute, with the entire melting process taking approximately 2–3 minutes.

This melted, viscous HDPE was then mixed with the synthesized IONPs. The compatibility of the IONPs with the HDPE in its melted state is crucial, as it ensures that the nanoparticles can be uniformly distributed within the plastic matrix. The mixed sample was then manipulated into a thin layer between two sheets of weighing paper using a small rolling pin. The composite was heated before being attached to the disposable cup layer.

Evaluation of Hydrophobicity

To conduct the contact angle experiment, distilled water droplets were applied to two surfaces: the regular plastic layer and the HDPE and IONP-infused layer. Magnified photos were captured from similar angles two minutes after the initial drops to observe any water penetration into each layer.

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