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ORIGINAL ARTICLE

Selective flotation separation of polycarbonate from plastic mixtures based on Fenton treatment combined with ultrasonic

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Abstract

As a main component of waste electrical and electronic equipment (WEEE) plastics, polycarbonate (PC) shows an important recycling significance. However, separating PC from WEEE plastics is difficult due to their similar hydrophobic surfaces and densities. Herein, a novel surface modification method using Fenton treatment combined with ultrasonic was proposed to selectively separate PC from acrylonitrile–butadiene–styrene (ABS) and polyvinylchloride (PVC) by froth flotation. The effects of surface modification and flotation conditions on the flotation recovery of plastics were investigated to determine the optimum separation conditions for PC. The optimum conditions are ultrasonic power 240 W, ultrasonic time 8 min, molar ratio (H_2O_2/Fe^{2+}) 100, hydrogen peroxide concentration 0.3 mol/L, pH 3, frother concentration 20 mg/L, stirring rate 1800 rpm and flotation time 4 min. Under optimum conditions, the recovery and purity of PC with different mass ratios exceed 97.97% and 99.18%, respectively. Contact angle and Fourier transform infrared spectroscopy were used to ascertain the mechanism of surface modification. The surface of PC becomes more hydrophilic due to the introduction of oxygen-containing groups induced by surface modification. Consequently, this study provides a practical surface modification method for the separation of PC from WEEE plastics, which will effectively promote the recycling of PC.

Keywords WEEE · Surface modification · Ultrasonic · Fenton · Plastic flotation

Introduction

Plastics have been extensively utilized in the electronics industry since they possess remarkable characteristics such as light, low cost and high chemical stability [1]. Driven by technological innovation, the service life of electronic products has gradually shortened, leading to a large accumulation of waste electrical and electronic equipment (WEEE or e-waste) [2]. According to "The Global E-waste Monitor 2020" issued by the United Nations, the total amount of e-waste generated globally reached 53.6 million tons in 2019 [3]. E-waste has become one of the fastest-growing waste streams in the world.

Plastics and metals are two main types of recyclable resources in e-waste. However, in the process of recycling e-waste, people pay more attention to the recycling of rare and precious metals, while the recycling of plastics is not getting enough attention. Plastics account for about 10–30% of WEEE [4]. The environment pollution caused by waste plastics is becoming more and more serious since plastics are difficult to degrade naturally. Most of the plastics separated from WEEE are disposed by landfill and incineration, while only 10% are recycled [5, 6]. Landfill occupies a lot of land resources, and it is easy to cause potential pollution to soil and groundwater [7, 8]. Incineration of plastics can release harmful substances, such as dioxins, hydrogen chloride and polycyclic aromatic hydrocarbons, which can enter the food chain through rainfall and threaten human health [9, 10]. Life Cycle Assessment (LCA) shows that replacing virgin plastics with recycled plastics can effectively reduce the negative impact of waste plastics on the environment [11]. Therefore, the recycling of waste plastics becomes an effective disposal method, which meets the requirements of sociallly sustainable development and cleaner production [12]. Unfortunately, plastic mixtures cannot be recycled

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directly due to the differences in additives, physical and chemical properties [13]. In other words, waste plastic mixtures must be separated into individual component before recycling.

As an important part of WEEE plastics, PC is very suitable for recycling [14]. However, the recycling of waste PC is challenging because it is usually mixed with other plastics, such as ABS and PVC [15]. In general, ABS, PVC and PC in WEEE can account for about 8 to 30%, 3–17% and 3–10%, respectively [16]. Currently, several prospective methods used for the separation of plastic including density separation [17, 18], electrostatic separation [19, 20], near-infrared (NIR) separation [21] and froth flotation [22, 23]. However, it is difficult to separate plastics with similar density by density separation. Electrostatic separation is not suitable for plastics with high humidity and small electrification differences. Near-infrared separation cannot sort dark plastics. In recent years, the application of flotation in plastic sorting has attracted widespread attention due to its cost-effective and high efficiency in the separation of plastic mixtures with similar properties [24]. The low surface energy of plastics determines that most plastics are naturally hydrophobic. Selective wetting of components to be separated is the key to realize plastic flotation separation [25–27]. In general, plastic flotation methods can be roughly divided into three categories according to the wetting mechanism: adsorption of wetting agents, physical regulation and chemical modification. Several wetting agents used in the flotation process include tea saponin [28], lignin sulfonate [29] and tannic acid [30]. Physical regulation methods used in the field of plastic flotation include Boiling treatment [31], plasma treatment [32], mild heat treatment [13], etc. And chemical modification methods include ammonia treatment [33], Fenton treatment [26], surface alkoxylation pretreatment [8], etc. The adsorption of wetting agents and physical regulation will not change the chemical composition of plastic while chemical modification focus on the surface reactions of plastic.

Advanced oxidation process (AOP), which is mainly based on the generation of highly reactive hydroxyl radicals, has been widely used in sewage treatment, soil remediation and landfill leachate [34, 35]. The common advanced oxidation processes include Fenton treatment, ozone oxidation, photochemical oxidation, etc. In recent years, the combination of Fenton treatment with other technologies has attracted more and more attention. Especially the synergistic effect of Fenton treatment and ultrasound technology can adequately decompose many organic substances which are difficult to degrade. Previous researches have shown that AOP is an effective surface modification method for plastic, which can achieve changes in hydrophilicity by oxidizing the surface of some plastics [14]. However, Fenton treatment combined with ultrasonic was never applied to the surface modification of plastics. Thus, it will be a meaningful attempt to study the influence of it on the surface of plastics.

Herein, we put forward a novel surface modification method using Fenton treatment combined with ultrasonic to separate PC from WEEE plastics. In this work, the effects of ultrasonic power, ultrasonic time, molar ratio (H_2O_2/Fe^{2+}), H_2O_2 concentration, pH, frother concentration, stirring rate and floatation time on floatability of plastics were investigated to identify the optimum conditions for separation. In addition, different mass ratios of PC were studied to determine the suitability of surface modification for diverse waste streams. Contact angle and Fourier transform infrared spectroscopy (FT-IR) were conducted to ascertain the mechanism of surface modification.

Materials and methods

Materials and chemicals

Plastic samples used in this study, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC) and polyvinyl chloride (PVC), were obtained from commercial source (SK, Holdings, Korea). The average density of ABS, PC and PVC in this study is 1.05 g/cm^3, 1.20 g/cm^3 and 1.35 g/cm^3, respectively. In addition, to avoid the influence of surface pollution and aging degree after consumption on flotation results, virgin materials were used. The colors of ABS, PC and PVC are different, which makes it easy to sort manually after flotation experiments. The plastic samples were smashed to particles with the size of 3–5 mm by a Miniature multifunctional crusher (DFT-200A, JIUPIN, China). According to the previous research, the optimum size fraction in plastic flotation was 1–5 mm [16, 36, 37]. Thus, the size of the plastic particle selected in this study was 3–5 mm. The obtained plastic particles were then washed with tap water and dried at room temperature (25 ± 2 ℃).

Ferrous sulfate ($FeSO_4{\cdot}7H_2O$) was obtained from Kermel Chemical Reagent Co., Ltd. in Tianjin, China. Hydrogen peroxide (H_2O_2, 30%) was purchased from Damao Chemical Reagent Factory in Tianjn, China. Dilute sulfuric acid and sodium hydroxide were used as pH adjusters. Terpineol was frother and tap water was the flotation medium in all flotation experiments. Terpineol was chosen as the frother because of its advantages of convenient preparation, low cost and strong foaming. All chemical reagents were of analytical grade.

Surface modification

ABS (5 g), PC (5 g) and PVC (5 g) were mixed manually and added to a 100 mL beaker containing 50 mL Fenton reagent. Then, surface modification was carried out in a numerical

control ultrasonic cleaner (KQ-300DE, Kunshan Ultrasonic Instrument Co., Ltd., China) with the power of 0–300 W, reaction time of 0–10 min and ultrasound frequency 40 kHz. After surface modification, plastic particles were washed three times with tap water, and then flotation experiments were performed to investigate the effect of related parameters in surface modification on the floatability of ABS, PC and PVC.

Flotation experiments

Flotation experiments were carried out on a single-slot flotation equipment (XFD-II, China). The detailed flotation device and the experimental process can refer to our previous article [38]. After flotation experiments, the plastic particles floated and submerged were collected, washed, dried at room temperature and weighed. The separation efficiency was evaluated by recovery and purity. The recovery and purity of ABS, PC and PVC can be calculated by Eqs. (1)—(4). It should be noted that the presented recovery and purity values in this study were average values of three experimental results.

$$R_{if} = \frac{M_{if}}{M_{if} + M_{is}} \times 100\% \quad (1)$$

$$R_{is} = \frac{M_{is}}{M_{if} + M_{is}} \times 100\% \quad (2)$$

$$P_{if} = \frac{M_{if}}{M_f} \times 100\% \quad (3)$$

$$P_{is} = \frac{M_{is}}{M_s} \times 100\% \quad (4)$$

where R_{if} and R_{is} are the recovery of floated products and submerged products of i samples, respectively; P_{if} and P_{is} are the purity of floated products and submerged products of *i* samples, respectively. M_{if} and M_{is} are the weight of floated products and submerged products of *i* samples, respectively. M_{f} and M_{s} are the weight of floated products and submerged products, respectively.

Surface characterization of plastic samples

To ascertain the mechanism of Fenton treatment combined with ultrasonic, contact angle and Fourier transform infrared spectroscopy (FT-IR) were conducted under optimum surface modification conditions. Contact angles of distilled water dropped on the plastic surface were measured with a contact angle measuring instrument (SL200KS, Kino Industry Co., Ltd., USA). Besides, the contact angle value of each plastic sample was an average of five measurements. The functional groups on plastic surface were researched by Fourier transform infrared spectrometer (IL8CERNGI, PerkinElmer, USA).

Results and discussion

The effect of surface modification on plastic flotation

Effect of ultrasonic power

The influences of ultrasonic power, ultrasonic time, molar ratio (H_2O_2/Fe^{2+}), H_2O_2 concentration and pH on the flotation recovery of ABS, PC and PVC were investigated and the results are shown in Fig. 1. It should be noticed that flotation experiments after surface modification were conducted under the conditions of frother concentration 50 mg/L, stirring rate 1800 rpm and flotation time 10 min.

As shown in Fig. 1a, ultrasonic power has no significant effect on the flotation recovery of ABS and PVC, which is maintained at approximately 95% and 97%, respectively. When the ultrasonic power is 0, the flotation recovery of PC is 81.87%, which means that it is difficult to separate PC from the other plastics (ABS and PVC) by Fenton treatment alone. However, the flotation recovery of PC decreases rapidly with the increase of ultrasonic power, and it decreases from 81.87% to approximately 3% when ultrasonic power increases from 0 to 240 W. The subsequent mechanism analysis shows that the contact angle of PC dropped obviously after surface modification, indicating the wettability of PC surface was enhanced. And the FT-IR analysis shows that the introduction of hydrophilic oxygen-containing groups (C=O and C–O) lead to the enhancement in wettability of PC surface. Detailed analysis can be seen in 3.4 mechanism of surface modification. The enhancement of wettability for PC surface reduced the flotation recovery drastically. Therefore, the optimum ultrasonic power for separating PC from plastic mixtures is 240 W.

Effect of ultrasonic time

As seen from Fig. 1b, the flotation recovery of ABS and PVC is insensitive to ultrasonic time, while that of PC decreases significantly with the increase of ultrasonic time. The flotation recovery of ABS, PC and PVC is about 99%, 97% and 99% without Fenton treatment combined with ultrasonic, which is mainly caused by the natural hydrophobicity of ABS, PC and PVC. The natural floatability of plastics refers to the floatability of plastic particles under the action of air bubbles without adding any frother. The natural floatability data of ABS, PC and PVC were presented in Fig. S1. As shown in Fig. S1, the

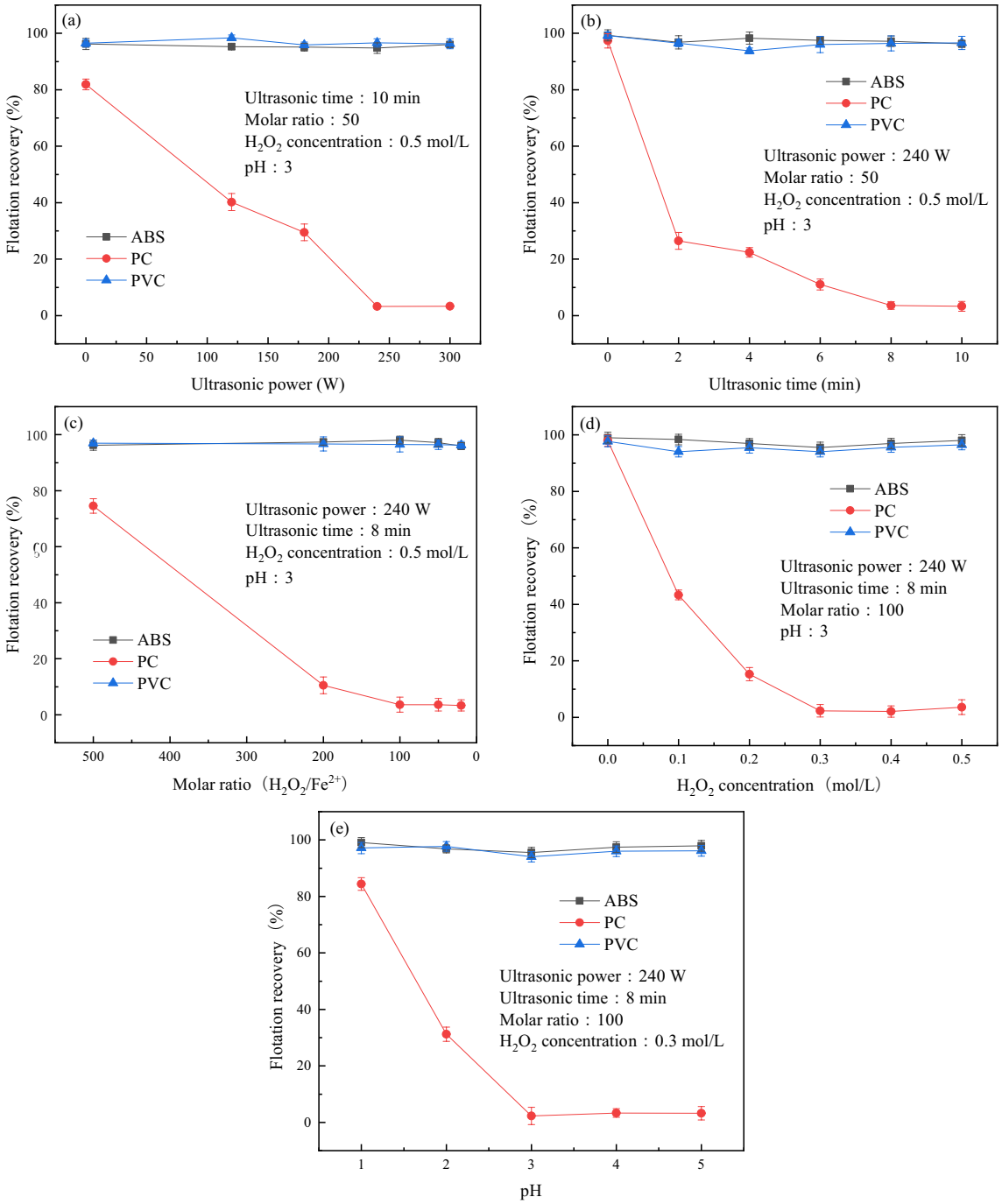

Fig. 1 The effect of **a** ultrasonic power, **b** ultrasonic time, **c** molar ratio (H_2O_2/Fe^{2+}), **d** H_2O_2 concentration and **e** pH on flotation recovery of ABS, PC and PVC. The flotation experiments after surface modification were conducted under the conditions of frother concentration 50 mg/L, stirring rate 1800 rpm and flotation time 10 min

natural floatability of ABS, PC and PVC is 94.89%, 85.33% and 71.98% respectively, indicating the descending order of the natural floatability of the three plastics is ABS, PC and PVC. Furthermore, the addition of frother is beneficial to promote the formation of a large number of tiny bubbles, which makes plastics exist in the form of floating products easily. The flotation recovery of PC decreases to the lowest value of about 3% when the ultrasonic time increases to 8 min, which means that surface modification can effectively transform the hydrophobic surface of PC into hydrophilic surface. The difference between PC and other plastics in floatability is the

largest at this moment. Therefore, the optimum ultrasonic time for separating PC from plastic mixtures is 8 min.

Effect of molar ratio (H_2O_2/Fe^{2+})

As seen from Fig. 1c, the flotation recovery of PC is remarkably affected by the decrease of molar ratio (H_2O_2/Fe^{2+}), while that of ABS and PVC is not affected. The flotation recovery of PC decreases from 74.54% to 3.61% when the molar ratio (H_2O_2/Fe^{2+}) decreases from 500 to 100, indicating that a significant fraction of PC submerged. The flotation recovery of ABS and PVC stays at about 98% and 97%, respectively. It can be explained that Fe^{2+} can catalyze H_2O_2 to produce ·OH. When the amount of Fe^{2+} is too low, it will limit the production rate of ·OH, and thus inhibit the oxidation reaction on the PC surface [39]. Therefore, the optimum molar ratio (H_2O_2/Fe^{2+}) for separating PC from plastic mixtures is 100.

Effect of H_2O_2 concentration

As seen from Fig. 1d, the flotation recovery of ABS, PC and PVC is close to 100% when the H_2O_2 concentration is 0. The results indicate that PC cannot be separated from plastic mixtures by ultrasonic treatment alone. The flotation recovery of PC decreases significantly to approximately 3% in the H_2O_2 concentration range of 0–0.3 mol/L, while the flotation recovery of ABS and PVC is insensitive to the change of H_2O_2 concentration. It shows that the floatability of PC was changed after surface modification, while ABS and PVC were not affected. Therefore, the optimum H_2O_2 concentration for separating PC from plastic mixtures is 0.3 mol/L.

Effect of pH

As seen from Fig. 1e, pH has no significant effect on the flotation recovery of ABS and PVC, which maintains at about 98% and 97%, respectively. The flotation recovery of PC is 84.41% when pH is 1. It is because that when the pH is low, H^+ will inhibit the reaction of H_2O_2 with Fe^{2+} and reduce the production of •OH. When the pH increases to 3, the flotation recovery of PC drops to the lowest value of about 3%. When the pH continues to increase from 3, the flotation recovery of PC has a slight upward trend. It can be explained that the increase of pH will form hydroxide precipitation in solution, resulting in a decrease in the oxidizing capacity of system [40]. Therefore, the optimum pH for separating PC from plastic mixtures is 3.

The effect of flotation conditions on plastic flotation

Effect of frother concentration

Under optimal surface modification conditions, the influences of frother concentration, stirring rate and flotation time on the floatability of ABS, PC and PVC were further investigated, and the results are shown in Fig. 2. Frother concentration has a great influence on the generation of homogeneous bubbles and further affects the stability of flotation [41]. As shown in Fig. 2a, with the increase of frother concentration, the flotation recovery of ABS and PVC gradually increases and reaches the maximum at 20 mg/L, while the flotation recovery of PC maintains at around 3%. Therefore, the optimum frother concentration for separating PC from plastic mixtures is 20 mg/L.

Effect of stirring rate

The effect of the stirring rate on plastic flotation separation is presented in Fig. 2b. The flotation recovery of ABS is not affected by the stirring rate, which maintains at about 99%. As for PVC, with the increase of stirring rate, the floatation recovery gradually increases to about 99% when the stirring rate increases to 1800 rpm. When the stirring rate is less than 1800 rpm, the flotation recovery of PC maintains at about 3%. However, when the stirring rate increases from 1800 to 2200 rpm, the flotation recovery of PC increases rapidly to 80.76%. Under the optimum conditions, PC surface is completely oxidized and air bubbles will not be adsorbed on its surface. However, at 1800 + rpm, the entire flotation system is in an enormously turbulent state and PC will float up under the action of mechanical entrainment due to its relatively low density. It is not good for the whole separation process. Therefore, the optimum stirring rate for separating PC from plastic mixtures is 1800 rpm.

Effect of flotation time

As shown in Fig. 2c, the flotation recovery of ABS and PVC increases sharply with flotation time. When flotation time increases to 4 min, the flotation recovery of ABS and PVC reaches about 99% and tends to be stable. However, the flotation recovery of PC maintains at around 3% in the range of 2–10 min. Therefore, the optimum flotation time for separating PC from plastic mixtures is 4 min.

Flotation separation of PC with different mass ratios

The content of different types of plastics in diverse waste streams varies greatly [36], and thus the effect of mass ratio on separation of PC was investigated to verify the feasibility for different waste streams. Plastic mixtures were treated under optimum surface modification and flotation conditions. The mass ratios of PC are set as 25%, 50% and 75%. In addition, the mass ratio of ABS and PVC is 1:1. The results are shown in Table 1. It should be noted that F-P and S-P in Table 1 represent floated products and submerged products, respectively. It can be seen from Table 1 that PC

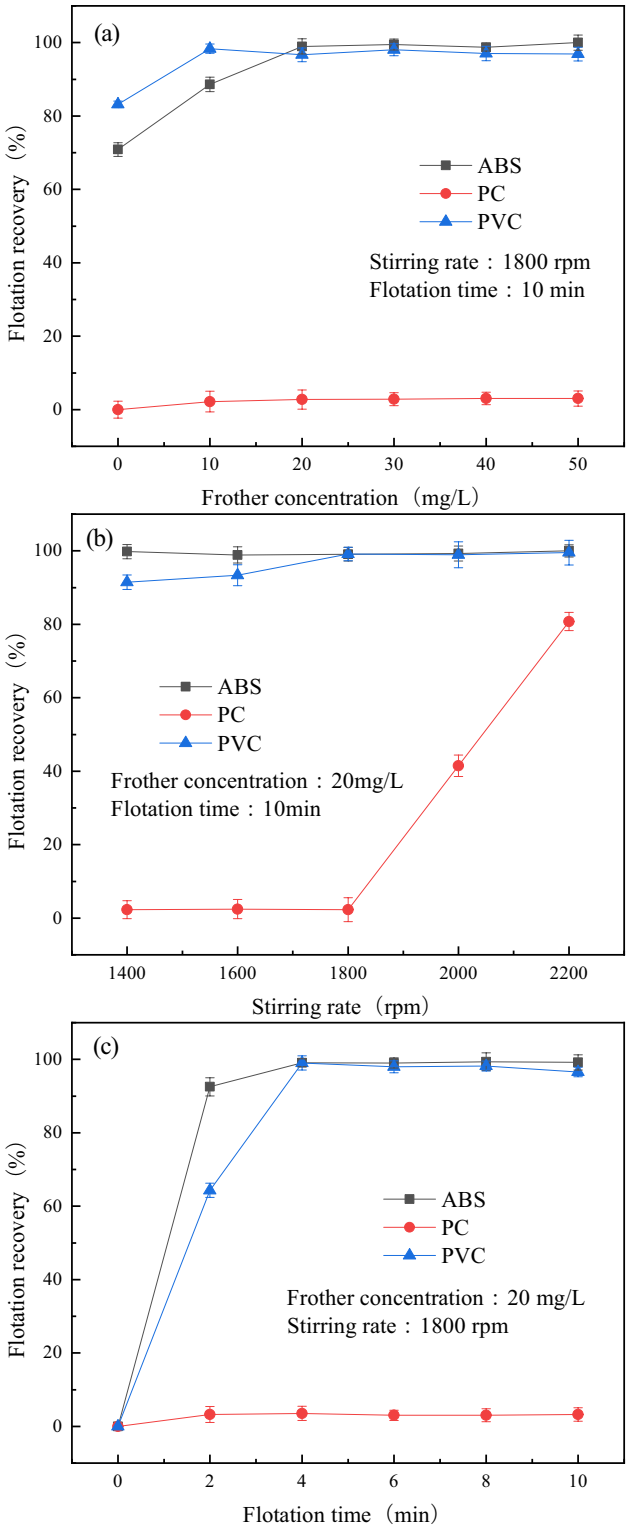

Fig. 2 The effect of **a** frother concentration, **b** stirring rate and **c** flotation time on flotation recovery of ABS, PC and PVC. The conditions of surface modification are ultrasonic power 240 W, ultrasonic time 8 min, molar ratio 100, H_2O_2 concentration 0.3 mol/L and pH 3

Table 1 Effect of mass ratio on recovery and purity of PC and others

Products	Yield (%)	Recovery (%)		Purity (%)	
		F–P	S–P	F–P	S-P
System 1	100	\	\	\	\
PC	25	1.99	98.01	0.66	99.18
ABS/PVC	75	99.73	0.27	99.34	0.82
System 2	100	\	\	\	\
PC	50	2.03	97.97	2.00	99.39
ABS/PVC	50	99.40	0.60	98.00	0.61
System 3	100	\	\	\	\
PC	75	1.77	98.23	5.12	99.47
ABS/PVC	25	98.43	1.57	94.88	0.53

F-P floated products, *S-P* submerged products, *ABS/PVC* the mixture of ABS and PVC

can be separated effectively from plastic mixtures with different mass ratios. The recovery and purity of PC exceed 97.97% and 99.18%, respectively. Especially in system 3, the recovery and purity of PC is 98.23% and 99.47%, respectively. Consequently, the separation of PC can be achieved effectively through surface modification and flotation process under different mass ratios conditions.

Reusability of surface modification solution

To minimize environmental pollution and reduce recycling costs, the reusability of surface modification solution was considered and the results are shown in Fig. 3. The experiments were conducted under the optimum conditions, but the surface modification solution was used repeatedly. In the first two uses of Fenton reagent, the recovery and purity of PC are maintained above 95%. At the second cycle, the recovery of PC drops significantly, indicating that the residual H_2O_2 concentration is decreased. At the 3rd, 4th and 5th cycles, the recovery of PC is less than 20%, which is due to the low or zero residual H_2O_2 concentration in the surface modification solution. The purity of PC gradually decreases with the number of cycles, which is related to the decrease in the recovery of PC. Therefore, in view of the reduction in separation efficiency of the second cycle and subsequent cycles, we suggest that the surface modification solution can be used twice.

Mechanism of surface modification

The mechanism of hydroxyl radical (·OH) production

The ·OH is an effective oxidizing factor in the system due to its strong oxidizing properties. The ways in which ·OH are generated and plastic surface are oxidized are shown in the following formulas (5–10). Ultrasound can induce

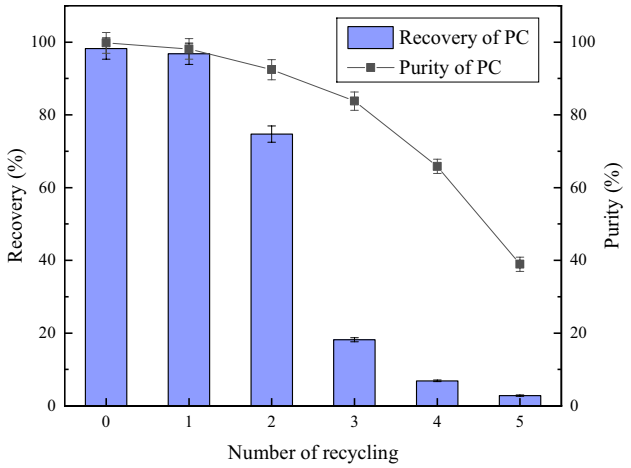

Fig. 3 Reusability of surface modification solution

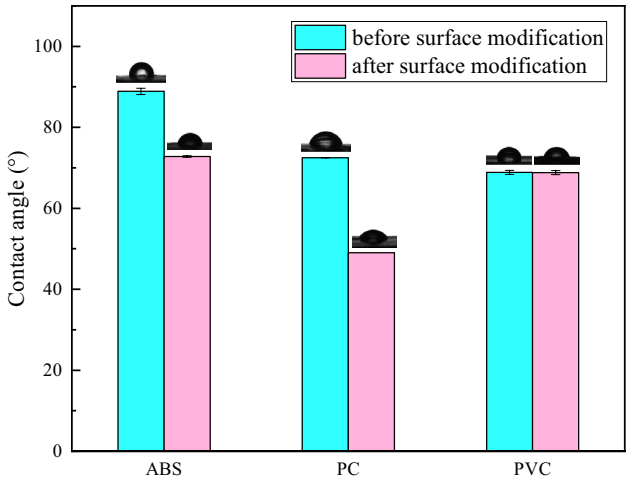

Fig. 4 Contact angle of ABS, PC and PVC before and after surface modification

the sonolysis of water molecules to produce ·OH [14]. At the same time, under acidic conditions, ferrous ions (Fe^{2+}) catalyze the decomposition of hydrogen peroxide (H_2O_2) to produce ferric ions (Fe^{3+}) and ·OH. The ferric ions can react with H_2O_2 to form Fe^{2+} and ·OOH, which will ensure the regeneration of Fe^{2+} and the continuous progress of the reaction.

$$H_2O + \text{Ultrasonic} \rightarrow \cdot OH + \cdot H \quad (5)$$

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \cdot OH \quad (6)$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + H^+ + \cdot OOH \quad (7)$$

$$RH + \cdot OH \rightarrow R\cdot + H_2O \quad (8)$$

$$R\cdot + H_2O_2 \rightarrow ROH + \cdot OH \quad (9)$$

$$\cdot OH + \text{hydrophobic surface} \rightarrow \text{hydrophilic surface} \quad (10)$$

The generated ·OH can be adsorbed on the surface of plastic and further react with it. According to the above formulas, organics (RH) can react with ·OH through hydrogen abstraction reaction, generating organic radicals (R·) with high reactivity which react with H_2O_2 easily [37]. Therefore, the surface of plastic (PC) can be oxidized and introduced some hydrophilic groups in the molecular structure of plastic, which will lead to the sedimentation of PC.

Contact angle analysis

To evaluate the change of surface hydrophilicity of ABS, PC and PVC, the contact angles of the plastic surface were measured before and after surface modification under the optimum conditions. As shown in Fig. 4, the contact angle of ABS decreases from 88.88° to 72.78° with the help of surface modification, indicating that the hydrophilicity of ABS is enhanced. It indicates that the surface of ABS may be oxidized. However, ABS exists in the form of floating products after the end of the flotation experiment. That's because the density of ABS is 1.05 g/m^3, which is similar to the flotation medium (1.00 g/m^3). Under the effect of low density and mechanical entrainment, ABS floats on the water. In terms of PC, the contact angle decreases from 72.51° to 49.02° after surface modification, indicating that its surface hydrophilicity is significantly increased, which is consistent with the sharp drop of flotation recovery of PC. As for PVC, the contact angles before and after surface modification are 68.88° and 68.80°, respectively. These results show that the hydrophilicity of PVC is almost unchanged, which is consistent with the fact that PVC keeps floating in flotation experiments.

FT-IR analysis

The essence of surface modification is the oxidation of hydroxyl radicals produced by the Fenton reagent. To detect the change of functional groups on the plastic surface after the combined treatment, FT-IR analysis was performed. As seen from Fig. 5a, the FT-IR spectra of untreated and treated ABS include adsorption bands at 698 and 758 cm^{-1} for bending vibration of C–H (mono-substituted benzenes), 1448 and 1491 cm^{-1} for stretching vibration of aromatic rings, 2919 cm^{-1} for stretching vibration of –CH_3 and 965 cm^{-1} for bending vibration of = C–H [33, 42]. The FT-IR spectra of untreated ABS include adsorption bands at 2236 cm^{-1} for stretching vibration of C≡N. However, after surface modification, adsorbing bands of C≡N is reduced

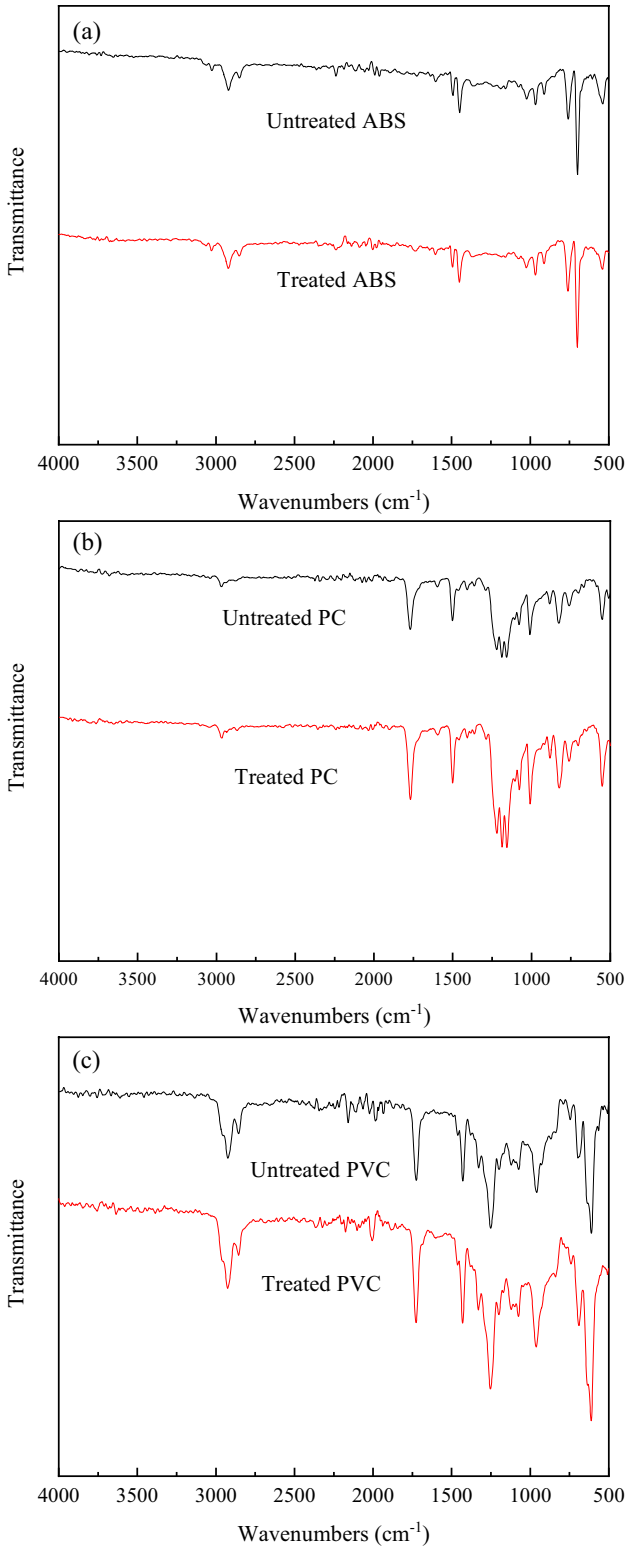

Fig. 5 FT-IR spectra of **a** untreated and treated ABS, **b** untreated and treated PC and **c** untreated and treated PVC

and stretching vibration of C = O at 1733 cm^{-1} is enhanced, indicating that the surface of ABS is oxidized and oxygen-containing functional groups are introduced [43]. The above results are also consistent with the reduction of the contact angle of ABS.

As seen from Fig. 5b, the FT-IR spectra of untreated and treated PC include adsorption bands at 825 cm^{-1} for bending vibration of C–H (mono-substituted benzenes), 1501 cm^{-1} for stretching vibration of aromatic rings, 2969 cm^{-1} for stretching vibration of $–CH_3$, 1220 cm^{-1} for stretching vibration of C–O and 1770 cm^{-1} for stretching vibration of C = O [7, 44]. In addition, it is obvious that the intensity of C–O and C = O peaks at wavenumbers of 1220 and 1770 cm^{-1} are enhanced after surface modification, indicating that oxygen-containing functional groups are introduced on PC surface. The introduced oxygen-containing functional groups are hydrophilic, which are expected to enhance the surface hydrophilic of PC.

As shown in Fig. 5c, the FT-IR spectra of untreated and treated PVC include adsorption bands at 695 cm^{-1} for stretching vibration of C–Cl, 2854 and 2923 cm^{-1} for stretching vibration of $–CH_2$, 1428 cm^{-1} for deformation vibration of $–CH_2$, 958 cm^{-1} for rocking vibration of CH_2, 1251 and 1328 cm^{-1} for bending vibration of C–H and 1095 cm^{-1} for stretching vibration of C–C [15, 45]. The FT-IR spectra of untreated and treated PVC show no significant changes, implying that surface modification has little effect on PVC.

Limitation and perspectives

This process is simple, stable and reliable. However, the limitation of this process may come from flotation behaviors and oxidation selectivity. At present, our research only stays in the laboratory stage and lacks practical application in the industry. The flotation behaviors of plastic particles in large-scale machine may different from laboratory-scale flotation machine. In the future, the flotation equipment and process can be improved, so as to establish a more complete flotation separation process. Moreover, when other plastic components are mixed in the plastic mixture (ABS, PC and PVC), its effectiveness needs further study. The strong oxidizing properties of the system may cause the surface of other plastic components to be hydrophilic and reduce the purity of PC, which can be resolved by multistage flotation separation combined with other methods.

Conclusion

In this study, we propose a novel surface modification method for plastic using Fenton treatment combined with ultrasonic, which realizes the selective flotation separation

of PC from other plastics (ABS and PVC). The optimum conditions of separating PC from other plastic mixtures are ultrasonic power 240 W, ultrasonic time 8 min, molar ratio (H_2O_2/Fe^{2+}) 100, H_2O_2 concentration 0.3 mol/L, pH 3, frother concentration 20 mg/L, stirring rate 1800 rpm and flotation time 4 min. Under different mass ratio conditions, the recovery and purity of PC exceed 97.97% and 99.18%, respectively. Surface modification solution can be used twice. The mechanism of surface modification was investigated by contact angle and FT-IR. The reduction of flotation recovery for PC is attributed to the decrease in contact angle and the introduction of hydrophilic groups (C = O and C–O) on the surface of PC, resulting in an increase in surface hydrophilicity. Therefore, this study can provide a scientific basis for promoting the recycling of PC in WEEE. The sources and types of waste plastics are various in our daily life, and hence it is necessary to verify the applicability of this method to the separation of PC in different waste streams in the future.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-022-01367-z.

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