Journal of Polymers and the Environment (2021) 29:3130–3144
https://doi.org/10.1007/s10924-021-02105-6

ORIGINAL PAPER

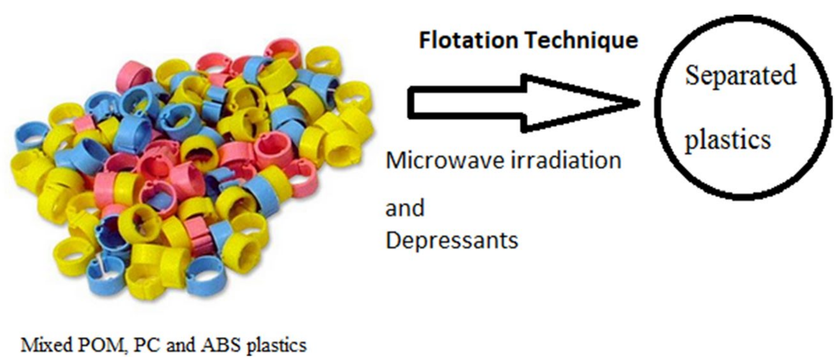
The Effect of Microwave Irradiation on the Flotation of the Selected Polymers as a Potential Solution for Plastic Recycling

Mojtaba Heidarpour[1] · Saeed Ostad Movahed[1] · Shahab Jourabchi[1]

Accepted: 22 February 2021 / Published online: 6 March 2021

Abstract
The separation of an individual plastic from a plastics mix is crucial in plastic recycling management. The selected plastics available in municipal and industrial wastes, including polycarbonate (PC), poly oxy methylene (POM), and acrylonitrile butadiene styrene (ABS) pre-irradiated with microwaves for different microwave power %'s at several irradiation times. The irradiated plastics subsequently conditioned with selected depressants with different concentrations before introducing into the flotation tank. The effects of the above-mentioned parameters evaluated on the float-sink behavior of the studied plastics. It revealed that the pre-microwave irradiation of the plastic surface was influential on the float-sink performance of the studied plastics. The microwave irradiation changed the numbers, capacity, and concentration of the active sites on the plastic surface. The microwave irradiation reduced θ (contact angle) values of the un-conditioned plastic surface with studied depressants for all used plastics resulted in increasing the hydrophilic property of the surface of the plastics. It concluded that different mechanisms, individually or together, involved for depressant adsorption–desorption on a plastic surface. The microwave pre-irradiation for some plastics and depressants was beneficial for plastic flotation whenever for other samples, it helped the plastic to sink at the bottom of the flotation tank. The suggested equations by Design-Expert® software to predict the plastic flotation % versus studied parameters conformed with experimental results appropriately.

Graphic abstract



Keywords Flotation · Plastic · Recycling · Microwave · Waste management

Introduction

The rapid growth of the end life used plastics in municipal waste streams became a critical issue for human life [1]. The accumulation of them in the environment is a potential threat for the ecosystem because several years of need for their degradation at ambient conditions. On the other hand,

✉ Saeed Ostad Movahed
s-ostad@um.ac.ir

1 Department of Chemistry, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran

recycling of plastics should done to save material resources, i.e., oil and coal [2]. Usually, in waste streams, we face a mixture of plastics. For re-using plastics and returning them to the production cycle, they should be separated from each other efficiently [3, 4]. Several separation methods already been developed, including density difference [5–7]. This technique is a cost-effective and simple method. However, it is not an effective technique because most municipal waste polymers have near densities with each other. Other methods used, namely, selective plastic dissolution [8–10] and electrostatic [11–13] had their individual drawbacks. The main drawbacks were the emittance of toxic organic solvents for the former and the expensive process for the latter. Hence, the lack of an economical, efficient and simple method for separating the individual polymer from a mixture of polymers observed.

The flotation separation method was recently proposed a comprehensive technique for the separation of commonly used municipal plastics [3, 4]. Although it was using for mineral ore purification for the last decades [14, 15], however, for plastic separation, is approximately a new idea and strategy. The basis of the mentioned method relies on the selective hydrophilicity alteration of the plastic surface, making a plastic float or sink in a liquid (water) media vessel. This alteration may accomplish by modification of the plastic surface physically, i.e., surface microwave irradiation, or by depositing a chemical (depressant) on the plastic surface. The researchers already studied the latter for separation of PVC-PET by using DIB and ELO [16], PVC-PET-POM by CaLS [17], PET-HDPE by DIB [18], PC-PS-POM using various depressants, including CaLS, TA, Terpineol, and PDGE [19] and ABS, HIPS, PC, PVC, and PET using NaCMC, Quebracho, SDS, SCMC, NP-7,DOP,DBS,DIB, LA, and TX-100 as useful depressants [20–24].

The microwaves, as electromagnetic irradiation, have frequencies between 300 MHz and 300 GHz with wavelengths from 1 mm to 1 m [25]. They have several applications in the industry, including rubber recycling (de-vulcanization) [26–28]. The microwaves are used as a source of energy to modify (change) the surface properties, i.e., the hydrophilicity of the plastic surface [29]. The reason refers to plastic surface functional group alteration after microwave irradiation. Also, the modification enables the plastic surface for more efficient depressant precipitation, i.e., physical adsorption and or chemical linkage (if any) through changing the roughness of the plastic surface.

So far, limited published papers available in the literature for microwave-assisted material flotation. Gan Cheng et al. [30] reviewed the lignite flotation by several techniques, including solid surface modification by microwave irradiation. Thanh Truc and co-workers [31] studied on wettability change of styrene content plastics in waste streams by using zinc oxide in combination with microwave irradiation. Mallampati et al. [32] separated PVC from ASR/ESR waste stream by flotation technique after surface amendment by microwave. They concluded that the amounts of hydrophilic functional groups, namely, carboxyl, ether, and hydroxyl increased on the PVC surface after microwave irradiation. The microwave irradiation used to ilmenite surface modification and consequent flotation by Irannajad and his co-workers [33]. It revealed that the microwaves were useful in changing the flotation behavior of the studied material. Hung et al. [34] developed a novel microwave-assisted potassium permanganate amendment technique to separate polycarbonate (PC) from poly methyl methacrylate (PMMA) and polyvinyl chloride (PVC) waste plastics by flotation. Other investigations also reported [35–39] on the float-sink behavior of the several plastics using various depressants, techniques, and liquid mediums.

To expand the outcomes of scientific research to economic commercial application, the used materials should have three magic characteristics, reasonable cost, accessible in commercial quantity, and less hazardous for the human body. Considering the above points, MC, TA, PVA, and PEG were selected as suitable depressants for study the float-sink behavior of the selected plastics [3, 4].

The effects of selected depressants, i.e., methylcellulose (MC), tannic acid (TA), polyvinyl alcohol (PVA), and polyethylene glycol (PEG), individually or in combination with each other on the flotation of available engineering plastics, polycarbonate (PC), acrylonitrile butadiene styrene (ABS) and Polyoxymethylene (POM) in municipal wastes at different operative conditions already studied [3]. In this study, the effects of plastic surface pre-microwave irradiation on the float-sink behavior of the same plastics with the same depressants were studied, and the results discussed. The commercial application of the results as a potential solution for efficient separation of the selected engineering plastics in waste streams was the main target of the study.

Experimental

Materials

Table 1 represents the specifications of the used plastics, polyoxymethylene (POM), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC). The polyvinyl alcohol (PVA, depressant, BP 20, LIWEI CHEMICAL CO. LTD, China), polyethylene glycol (PEG, depressant, PEG-400, Shree Chem, India), methylcellulose (MC, depressant, 274,429 Sigma, average molecular weight, 40,000, SIGMA ALDRICH, USA), methyl isobutyl carbinol, and tannic acid (TA, depressant, 100,773, Merck, Germany) were prepared and used. They initially pre-treated with de-ionized water, and after drying, they were used for further flotation tests.

Table 1 The specifications of the used plastics, polyoxymethylene (POM), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC)

Plastic	POM	ABS	PC
Density (g/cm^3)	1.41	1.07	1.20
Surface tension (mN/m)	44.6	42.7	42.9
Granule shape	Sphere	Sphere	Sphere
Diameter (mm)	4	4	4
Supplier	Korea	Iran	Korea

Equipment and Testing Procedure

A laboratory microwave apparatus (GMO-530, Gosonic) with a maximum (100%) output power of 900 W, frequency of 2000 MHz, and internal capacity of 30 L was used. A total of 60 granules of the mixed plastics (20 from each plastic) were introduced to microwave apparatus at different output powers for different irradiation times before conditioning with studied depressants at different concentrations for 15 min. The total conditioned samples were introduced into the flotation tank subsequently. The floatation % of a plastic was calculated as:

$$Floatation\% = \frac{floated\ granules}{20} \times 100$$

Each test repeated three times, and the median value reported. The employed flotation tank and test procedure are already explained [3, 4]. The dimensions of the glass-made flotation tank were 20 cm (diameter) by 80 cm (height). The flotation tank is equipped with an air blowing system (13 cm circular air distributor diameter) with 4 L/minute as air bubble flow rate. The flotation time kept at two minutes. Figures 2–9 represent the flotation % of used plastics, POM,PC, and ABS un-conditioned and conditioned with different concentrations of depressants, TA,PEG,PVA,and MC without and with microwave irradiation at different microwave power %'s and irradiation times. The contact angle (θ) for a water droplet on the surface of the plastic was measured by a stereo microscope, SZH10 equipped with an Olympus DVP1 camera with 25X magnitude.

Results and Discussion

The depressants temporarily adsorb on the plastic's surface in different ways depending on their chemical natures and plastic surface chemical structure. This process alters the hydrophobic or hydrophilic properties of the plastic surface resulting in float or sinks of a selected or a group of plastics in a floatation media (here, tap water) from a plastic mix. The float-sink behavior of plastic in a liquid media with a selected depressant also depends on the surface characteristics of the plastic, including surface roughness and the type and concentration of the probable attached functional groups on the plastic surface. However, it may depend on the plastic particle shape, density and size (diameter), air bubble coverage on the particle surface and air bubble rate and size [40].

The microwave irradiation as an economical and environment-friendly technique for surface modification of the polymers was already accepted [41–44]. The microwave irradiation may change the roughness and morphology of the plastic surface, facilitate or de-facilitate the depressant precipitation (adsorption) on the surface depending on the processing condition. It also alters the concentration and type of the probable attached functional groups on the polymer surface [43]. Figure 1 illustrates the SEM images for the surface of POM and PC without and with 100% microwave power %. As observed, microwave irradiation was influential on the plastic surface roughness sensitively. The microwave irradiation reduced the surface roughness and smoothened the plastic surface. This surface modification alters the adsorption–desorption process of the depressants on the plastic surface in different ways depending on the operation condition.

The Effect of Microwave Power % at Different Depressants Concentrations on the Flotation of the Selected Plastics

The contact angle, θ for a water droplet on the surface of the plastic without any depressant conditioning measured without and with microwave irradiation with 60% power for 20 s. The corresponding θ values for POM, PC, and ABS were 113.1 and 108.8, 106.8 and 102.4, and 113.2 and 108.3. As observed, the microwave irradiation reduced θ values of the plastic surface for all used plastics before conditioning with a depressant. It means the microwave irradiation was effective in increasing the hydrophilic property of the surface of the plastics. This fact was reconfirmed when the reader compares the correspondent flotation % values reduction from 70 to 35, 75 to 40, and 85 to 80% for POM, PC, and ABS (Figs. 2–9), respectively.

The microwave power % selected as a criterion for the assessment of the rate of microwave irradiation on the plastic surface alteration. Figures 2–5 depict the POM, PC, and ABS flotation % at different depressant concentrations at various microwave power %'s. The flotation tank media pH kept as 6.5 at ambient temperature. The irradiated plastics were irradiated by microwaves for 20 s before introducing to the flotation tank. As observed, in general, microwave

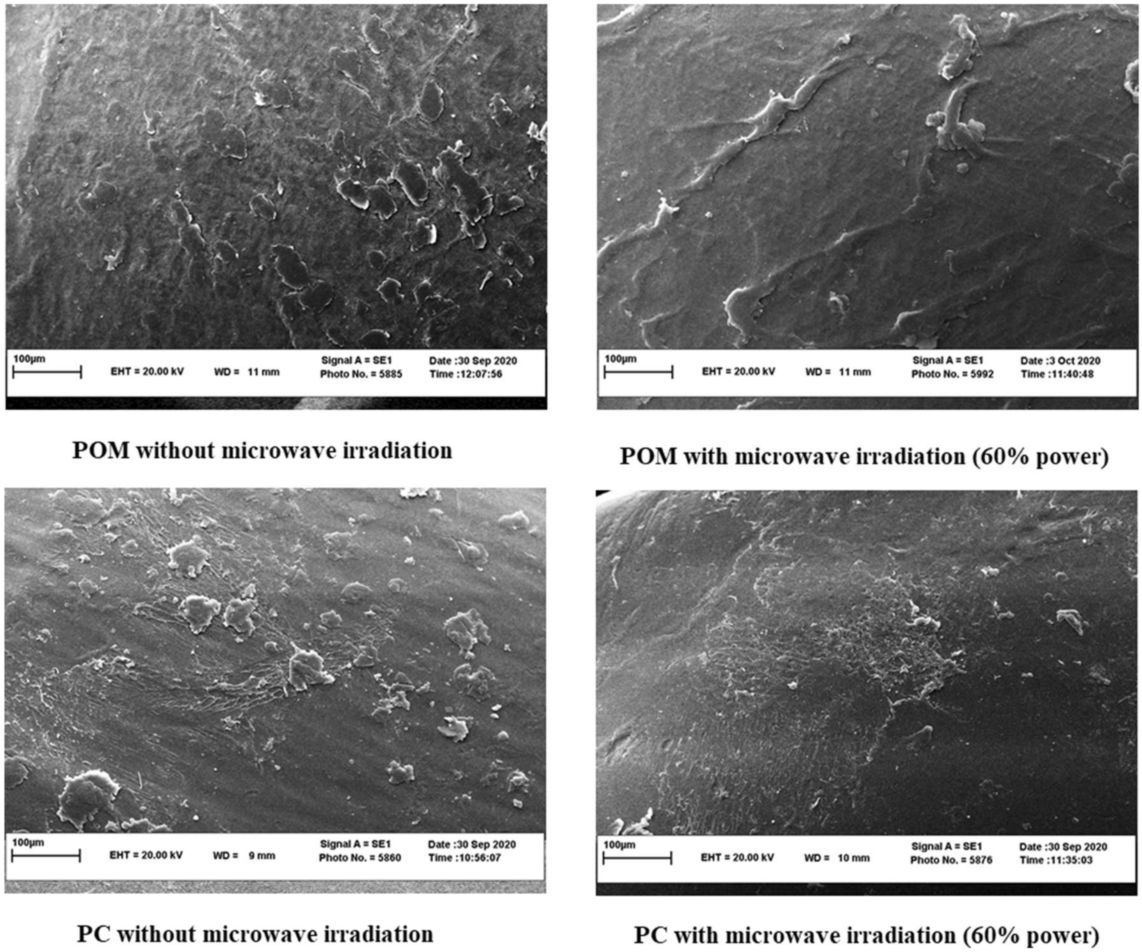


Fig. 1 The SEM images of POM and PC without and with 100% microwave power %

irradiation was effective on float-sink of all studied plastics for all used depressants with different values and trends. For some powers and depressants, the plastic flotation improved, while in other cases, it was not beneficial for plastic flotation, and the most plastics sunk at the bottom of the flotation tank. As an illustration, the maximum flotation of POM shown in Fig. 2 for different TA concentrations, 400, 800, 1200, 1600, and 2000 mg/L observed for 60% microwave power % with the values of 90,90,75,70 and 85%, respectively. The corresponding value without using depressant (TA) was 70%. Unlike POM, Fig. 2 shows sharp deterioration of PC and ABS flotation with increasing TA concentration. At the same power % (60%), the flotation % of PC and ABS were reduced from 55 and 90% without conditioning with TA to the values of 5 and 20% for 1200 mg/L TA concentration, respectively. The minimum flotation values at different power %'s belong to the same TA concentration (1200 mg/L) ranged from 5 to 25% and 15 to 20% for PC and ABS, respectively. However the minimum PC flotation % was 5% at 20,40,60% microwave power % for 1200 mg/L TA concentration and 100% power for 2000 mg/L TA concentration (Fig. 2). The same minimum value also was observed for ABS at 40% power and 2000 mg/L TA concentration. The maximum flotation value for POM observed at 20% power for 1200 and 1600 mg/L TA concentration with a value of 90%.

As described earlier [3], lower floatation values for PC when compared with POM refers to stronger bond strengths between the former in comparison with the latter with TA molecules.

Because TA has numerous hydroxyl groups in structure, it hydrolyzes in water rapidly. When conditioned PC and POM with TA immerse in liquid media (water), the rate of desorption of adsorbed TA molecules on the POM surface was more rapid than those of the PC. Hence, the hydrophilicity property of conditioned POM reduces, and more POM granules float on the surface of the flotation tank.

For the description of depressant adsorption on a plastic surface, the reader should have a deep understanding of the adsorption–desorption process. The following points are the most important factors which affect the type and amount of depressant adsorption on a plastic surface [45–47]:

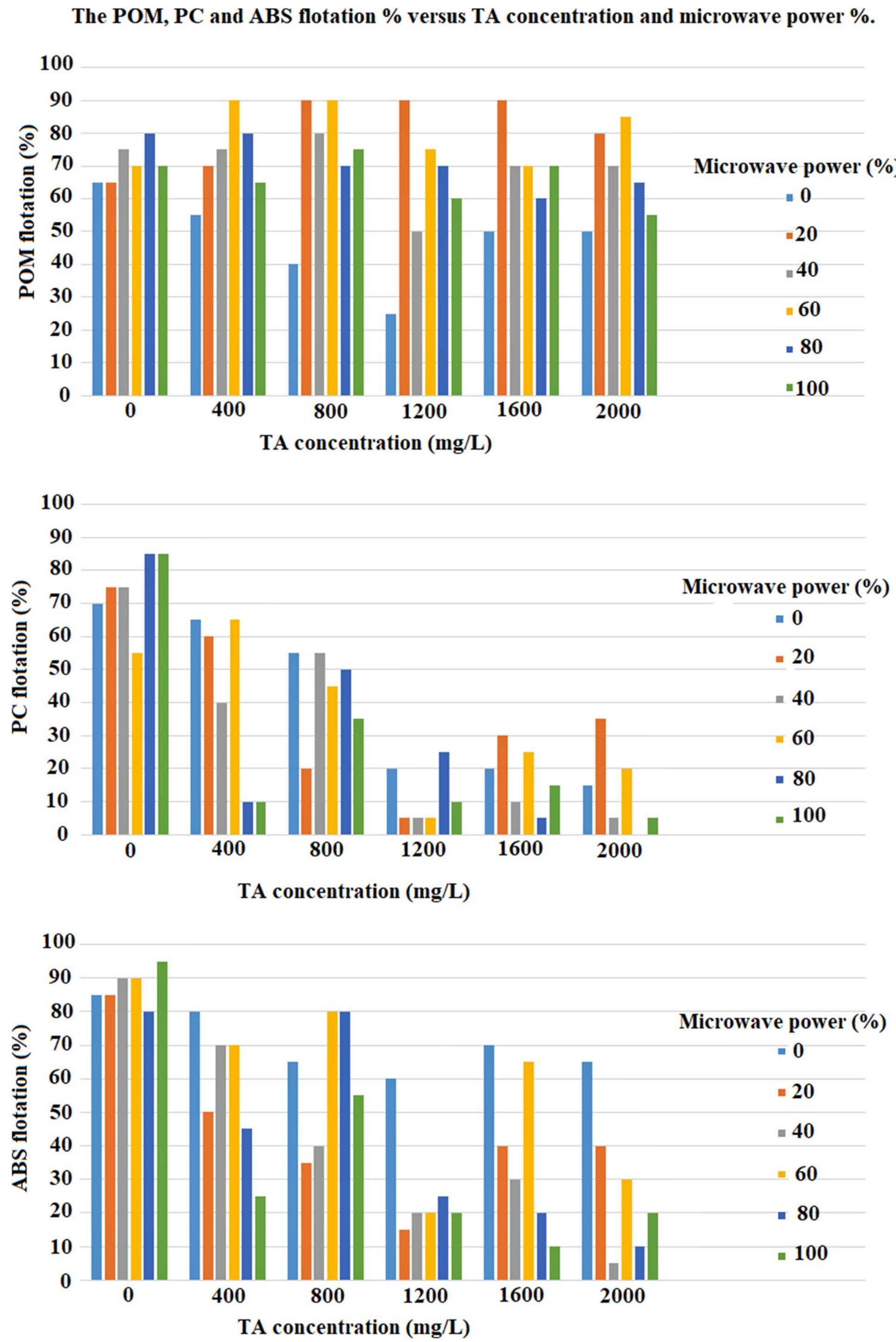


Fig. 2 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of tannic acid (TA) for various microwave power %'s. The flotation tank media pH kept as 6.5 at ambient temperature. All plastics were irradiated by microwaves for 20 s before introducing to the flotation tank

a) The numbers of active sites on the plastic surface
b) The number of depressant molecules adsorbed by an individual active site.
c) The difference between the enthalpy of adsorption of different active sites
d) The equilibrium constant for adsorption and desorption processes
e) The activation energy of adsorbed depressant
f) The Gibb's free energy of the adsorption process
g) The interaction between depressant molecules with each other and also with the molecules on the surface of the plastic.

As observed, the microwave irradiation may be effective on all or some of the above factors. The authors believe the microwave irradiation was more effective on the numbers, capacity (mono or multilayer adsorbed depressant molecule), and concentration of the active sites. However, the more thorough studies should done on this matter in the future.

Figure 3 shows remarkable flotation for all studied plastics when irradiated by microwaves and subsequent conditioning with PEG. The values for POM ranged between 65% for the sample without PEG and microwave irradiation to 95% for PEG concentration of 1600 mg/L at 60% microwave irradiation power. The correspondent values for PC were 55%, without PEG at 60% power to 90% for 800 and 1200 mg/L PEG without microwave irradiation. Also, the corresponding values for ABS were 70% for 2000 mg/L PEG at 40% microwave irradiation to 100% for 1200 & 1600 mg/L PEG without microwave irradiation.

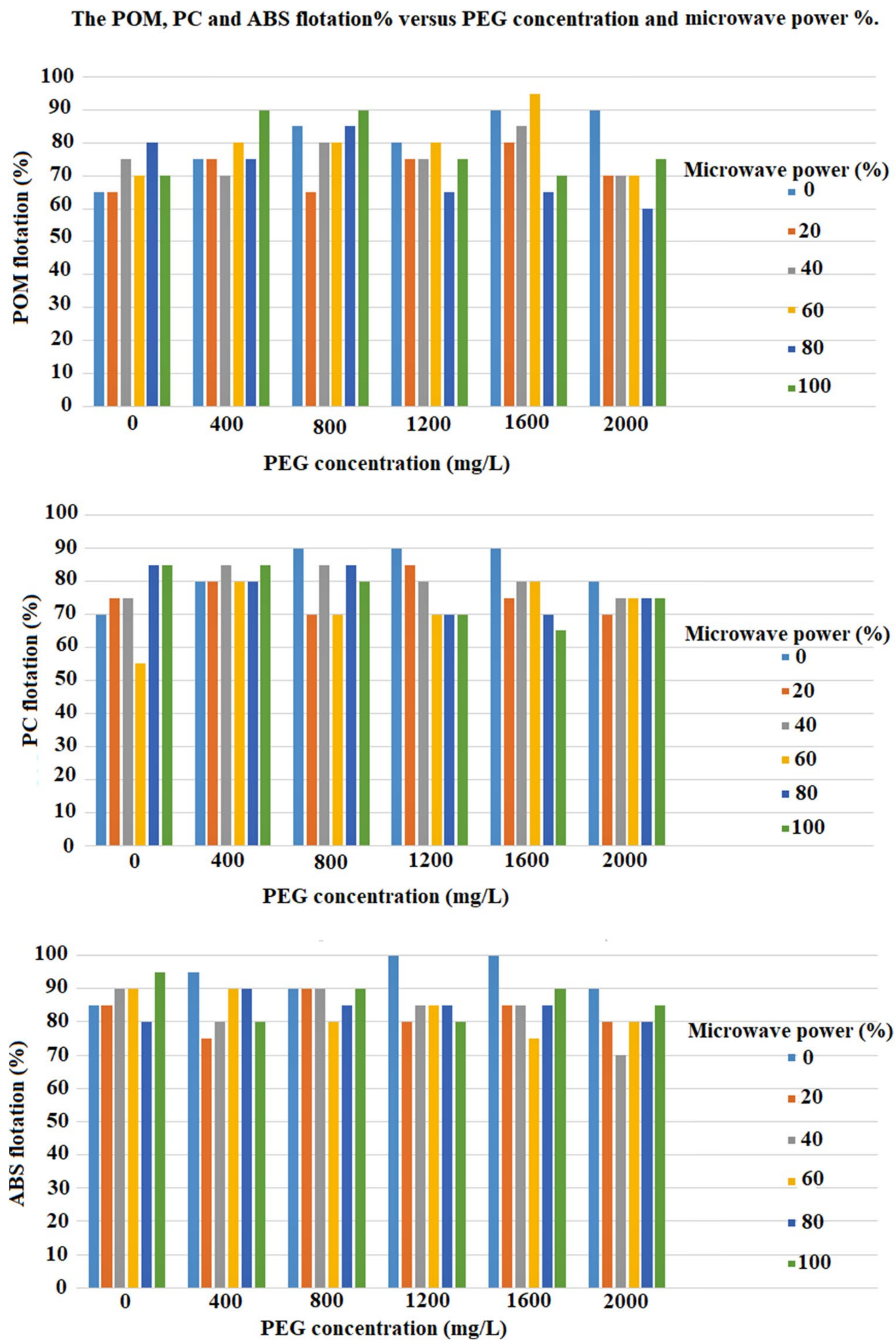


Fig. 3 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of polyethylene glycol (PEG) for various microwave power %'s. The flotation tank media pH kept as 6.5 at ambient temperature. All plastics were irradiated by microwaves for 20 s before introducing to the flotation tank

It seemed microwave irradiation was not beneficial for PC flotation, especially for PEG concentrations exceeding the value of 800 mg/L. The same fact was true for PEG concentrations over 400 mg/L for ABS flotation (Fig. 3). However, microwave irradiation was beneficial for the flotation of all plastics (POM, PC, and ABS) for samples without conditioning with PEG.

Figure 4 clearly showed a combination of microwave irradiation and conditioning PC and ABS with PVA had an adverse effect on their floatation and caused them to sink on the bottom of the flotation tank. It seemed microwave

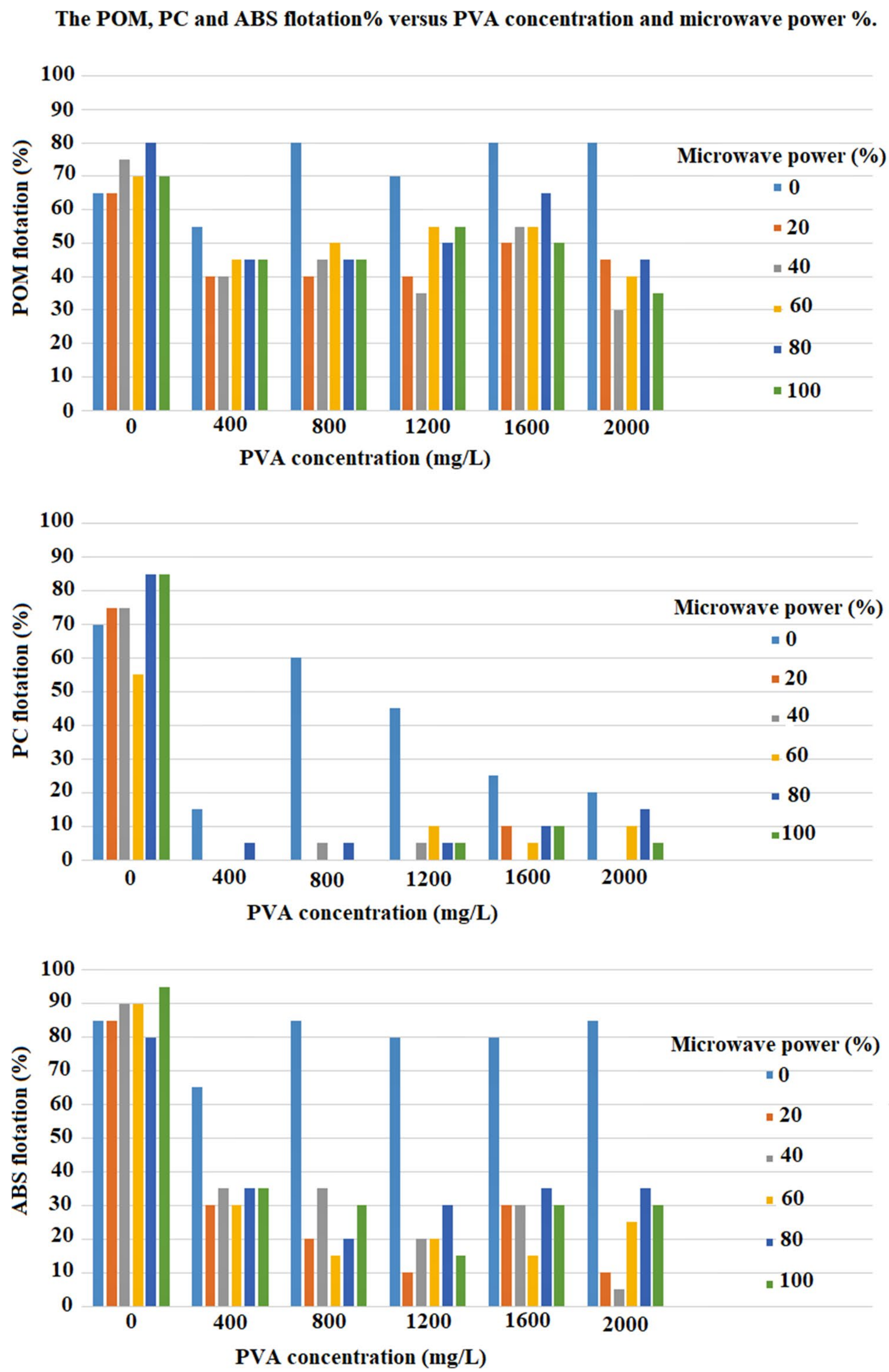


Fig. 4 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of polyvinyl alcohol (PVA) for various microwave power %'s. The flotation tank media pH kept as 6.5 at ambient temperature. All plastics were irradiated by microwaves for 20 s before introducing to the flotation tank

irradiation motivated active sites on the plastic surface and increased the adsorption capacity of the PVA on the surface. The adsorption of PVA reduced the hydrophobic property of the PC and ABS surfaces. The maximum and minimum PC flotation were observed at 100% power without PVA with the value of 85% and various power %'s for 400 and 800 mg/L PVA without flotation (0%), respectively. The corresponding values for ABS were 85% without PVA and microwave irradiation and 5% at 40% power for 2000 mg/L PVA, respectively. The POM flotation was less affected by PVA conditioning and microwave irradiation than those values for PC and ABS. The flotation of POM reduced from 65 to 30% when plastic granules were irradiated at 40% power and conditioned at a 2000 mg/L PVA solution. Figure 5 represents the flotation of POM, PC, and ABS at different microwave irradiation powers for various MC

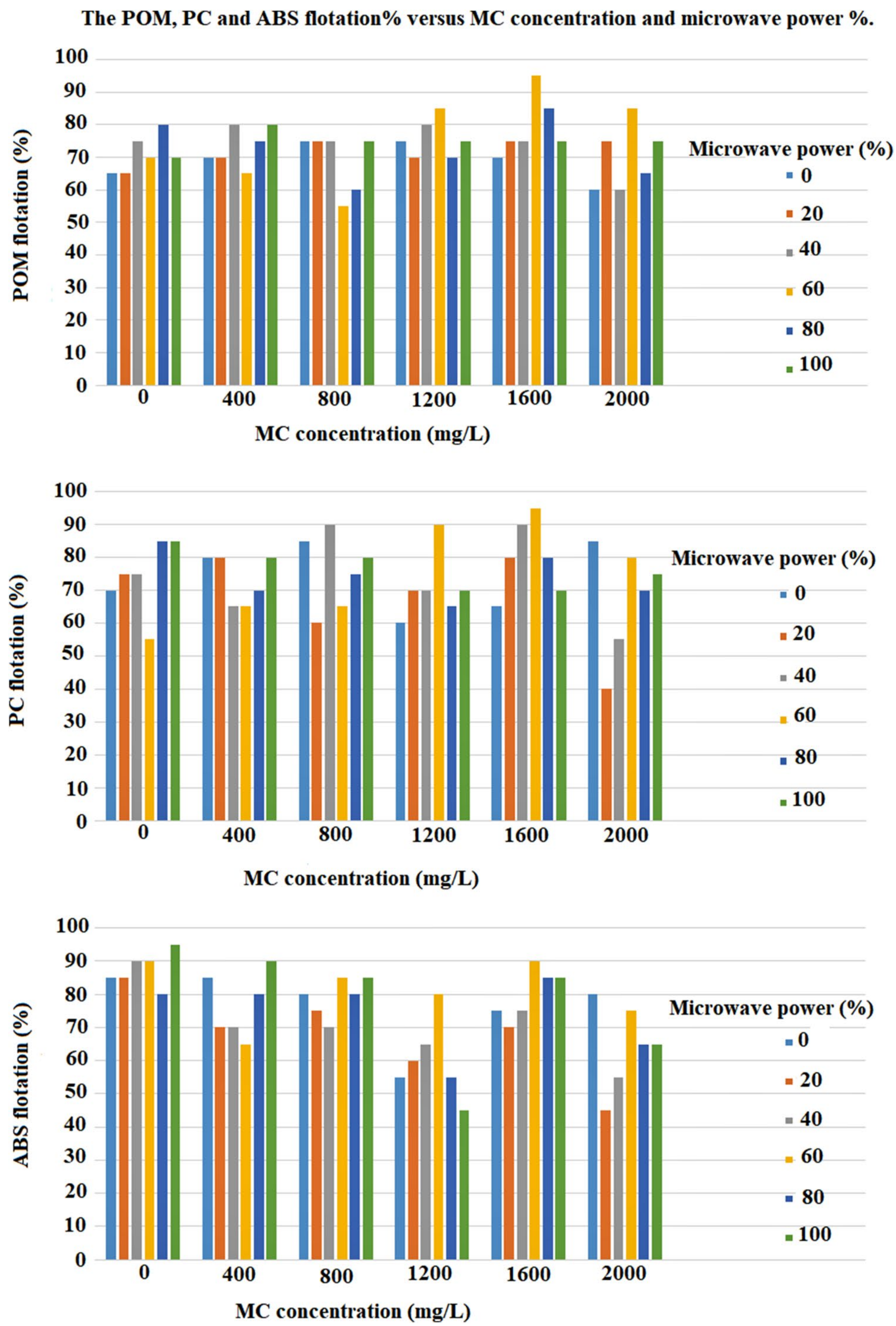


Fig. 5 The poly oxy methylene (POM), polycarbonate (PC) and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of methylcellulose (MC) for various microwave power %'s. The flotation tank media pH kept as 6.5 at ambient temperature. All plastics were irradiated by microwaves for 20 s before introducing to the flotation tank

concentrations. As observed, there was no regular trend, and the flotation had different values depending on the MC concentration and microwave power %. The POM, PC and ABS flotation ranged from 55% (60% power, 800 mg/L MC) to 95% (60% power, 1600 mg/L MC), from 40% (20% power,2000 mg/L MC) to 85% (without irradiation for 800 mg/L MC) and 45% (20% power, 2000 mg/L MC) to 95% (100% power without MC), respectively.

It concluded that a combination of microwave irradiation and depressant concentration was effective on the floatation of the studied plastics with different adsorption mechanisms.

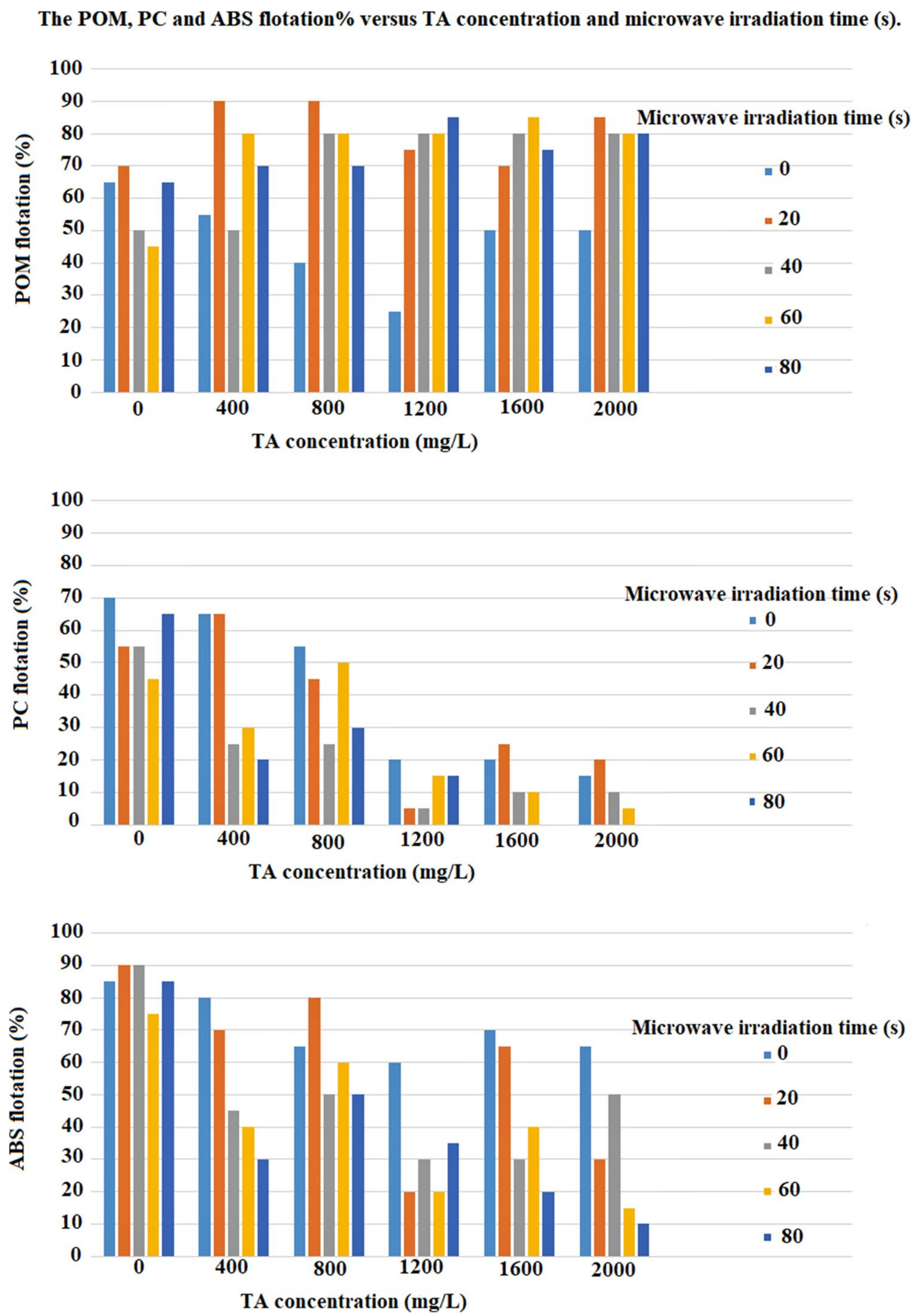


Fig. 6 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of tannic acid (TA) for various microwave irradiation times. The flotation tank media pH kept as 6.5 at ambient temperature. The microwave power was 60%

The Effect of Microwave Irradiation Time at Different Depressants Concentrations on the Flotation of the Selected Plastics

Figures 6–9 depict the flotation of studied plastics, POM, PC, and ABS at different concentrations of depressants, TA, PEG, PVA, and MC for various microwave irradiation times. The flotation tank media pH kept as 6.5 at ambient temperature. The microwave power selected as 60%. As observed, the flotation of POM benefited when it was irradiated by microwave before conditioning with all studied depressants. However, increasing the time of irradiation was beneficial for POM flotation for TA and MC concentrations over than1200 and 2000 mg/L, respectively (Figs. 6 and 9). For lower TA and MC concentrations, there was not any distinguished trend for the flotation improvement of this plastic. Unlike TA and MC, increasing the irradiation time deteriorated the POM flotation for conditioned plastics with PEG and PVA for depressants concentrations over 1600 mg/L. For lower PEG and PVA concentrations, the situation more

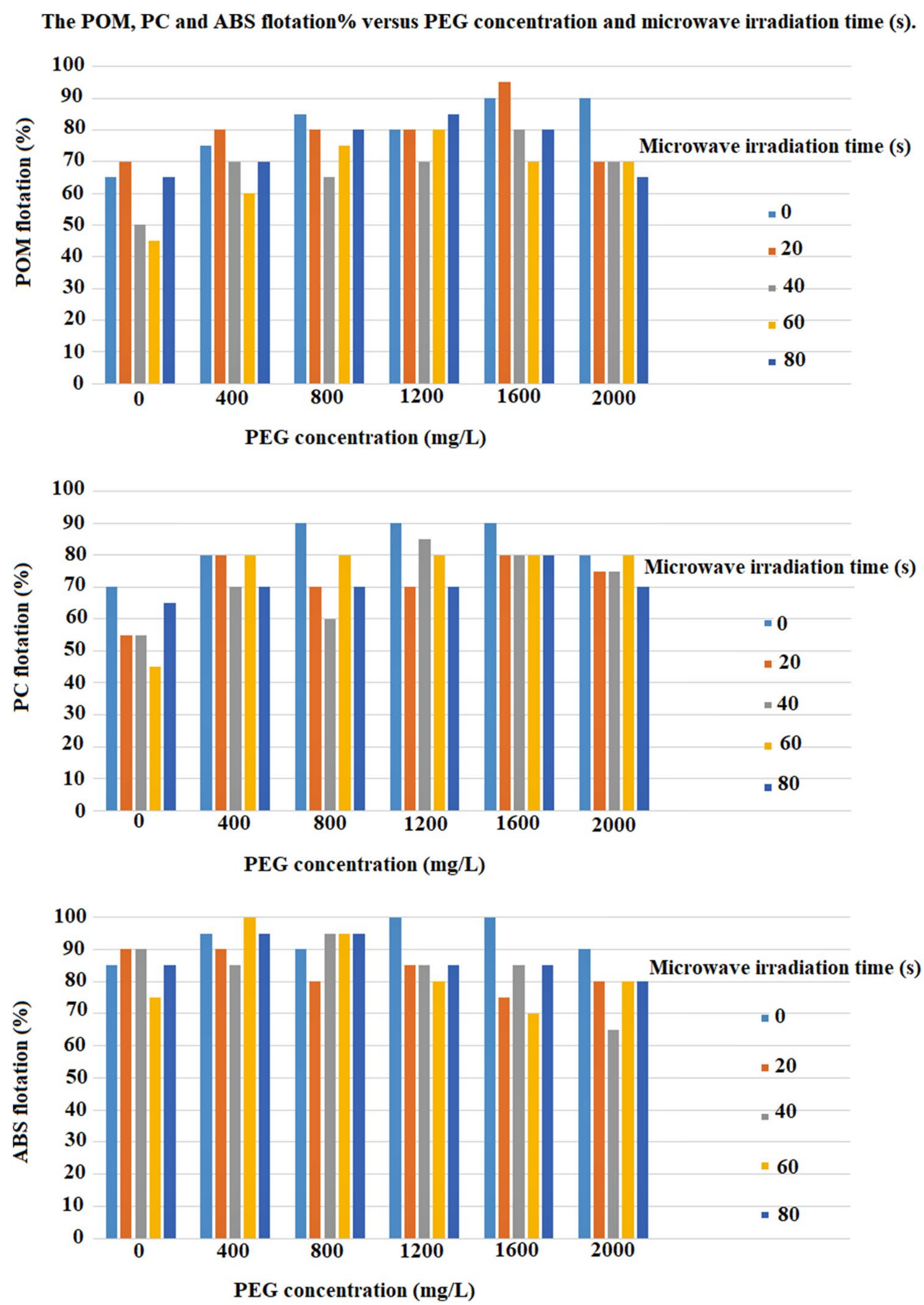


Fig. 7 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of polyethylene glycol (PEG) for various microwave irradiation times. The flotation tank media pH kept as 6.5 at ambient temperature. The microwave power was 60%

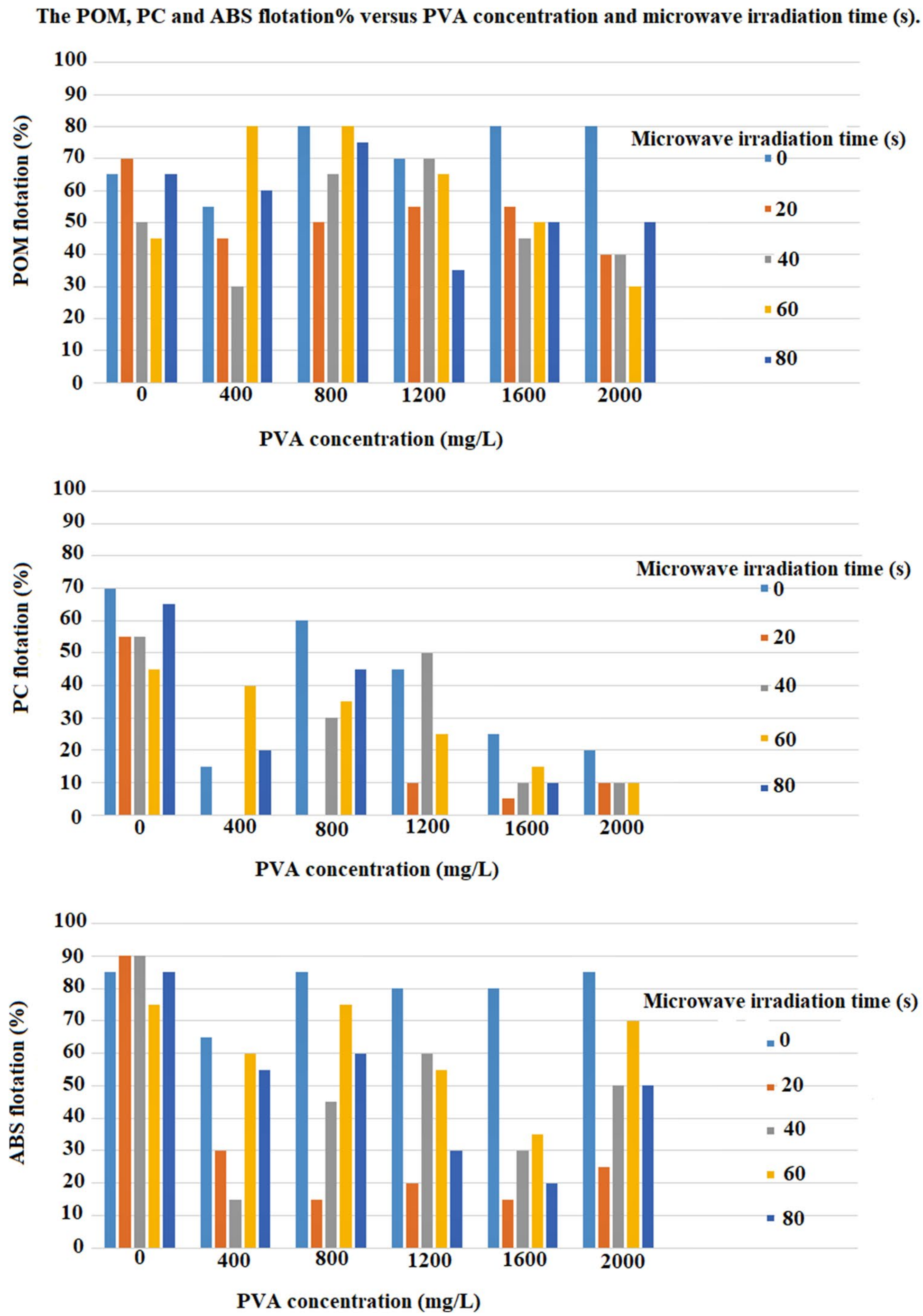


Fig. 8 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of polyvinyl alcohol (PVA) for various microwave irradiation times. The flotation tank media pH kept as 6.5 at ambient temperature. The microwave power was 60%

or less was the same as TA and MC (Figs. 7–8). The maximum and minimum POM flotation % 's were 95 and 25% with 20 (1600 mg/L PEG) and 80 (2000 mg/L MC) second irradiation time and 1200 mg/L TA concentration without microwave irradiation, respectively.

Figures 7 and 9 clearly show the lowest flotation variation for conditioned PC with PEG, and MC at studied irradiation times, 20, 40, 60 and 80 s. Interestingly, sensible flotation reduction was observed for conditioned PC with TA and PVA when irradiation time increased from 20 to 80 s (Figs. 6 and 8). The highest and lowest PC flotation %'s belonged to 1200 mg/L MC concentration with 20 s irradiation time and 1600 and 2000 mg/L TA concentration with 80 s irradiation time with the values of 95 and 0%, respectively.

The ABS flotation %'s did not influence by increasing irradiation time for un-conditioned samples sensitively. The values ranged between 75 to 90%. The above-mentioned fact more or less was true for conditioned ABS samples with PEG and MC at different irradiation times. The ABS flotation values ranged between 75 to 100%.

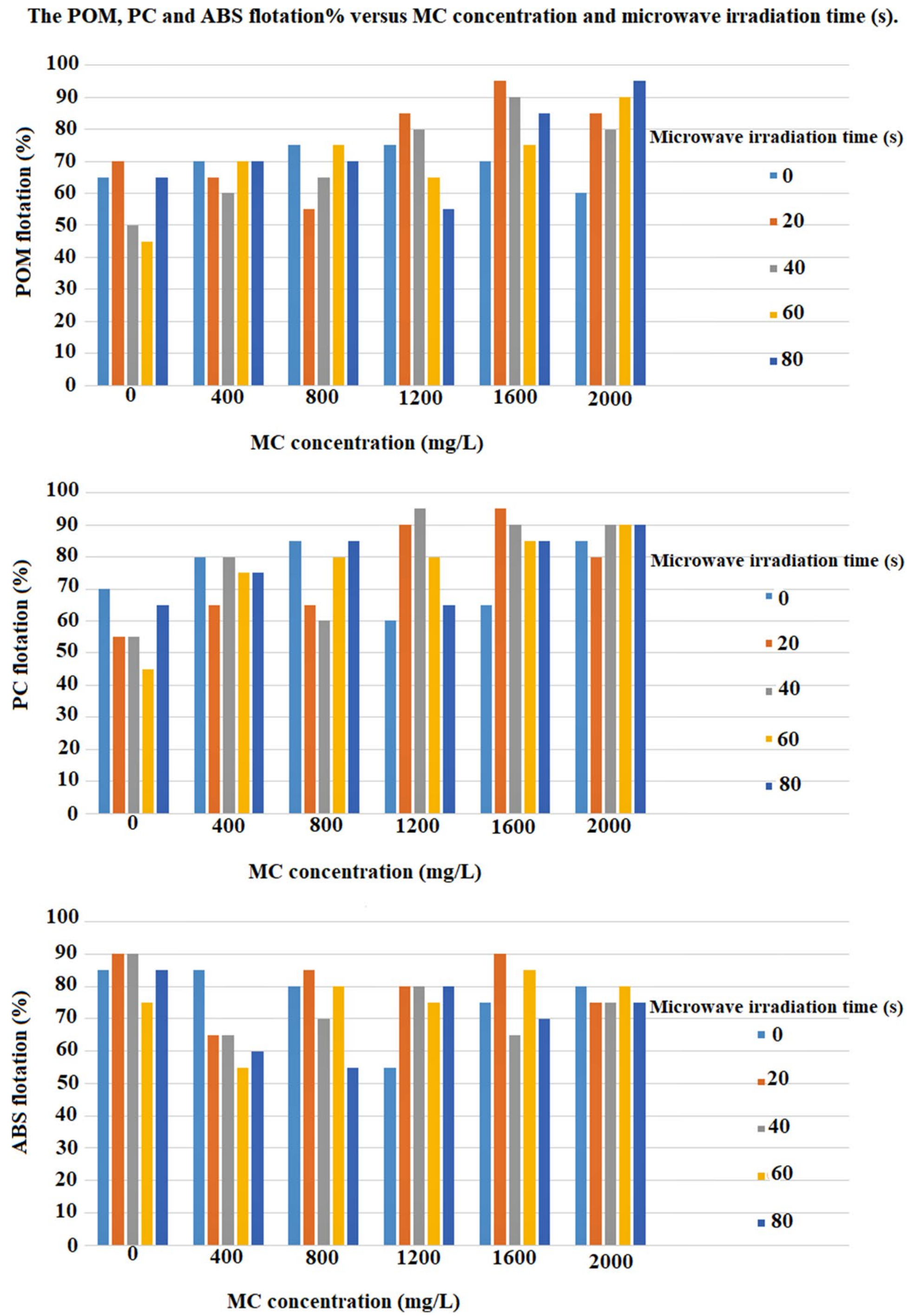


Fig. 9 The poly oxy methylene (POM), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) flotation at different concentrations of methylcellulose (MC) for various microwave irradiation times. The flotation tank media pH kept as 6.5 at ambient temperature. The microwave power was 60%

However, for conditioned ABS samples with TA and PVA the flotation range was extended to 10 to 85%. The highest and lowest flotation %'s belonged to 2000 mg/L PVA without microwave irradiation and 2000 mg/L TA for 80 s irradiation time.

From a thermodynamic viewpoint and for spontaneous adsorption, the sign of Gibbs free energy change in Eq. 1 should not be positive [3]:

$$\Delta G_{ad} = \Delta H_{ad} - T\Delta S_{ad} \quad (1)$$

where ΔG_{ad}, ΔS_{ad}, ΔH_{ad} and T were Gibbs free energy, entropy and enthalpy changes of the system during adsorption, and absolute temperature, respectively. It seemed, the microwave irradiation influenced the entropy change of the system by changing the active sites on the plastic surface. If microwave irradiation increases the entropy of the system,

Table 2 The suggested equations by a design of experiment software (Design-Expert® statistical software) for floatation % of studied plastics versus microwave power % (P), used depressant concentration (C, mg/L), and microwave irradiation time (T, second)

Depressant	Polymer	Equation
TA	POM	Floatability (%) $= 40.81056 + 0.632210P + 0.002168\ C + 0.792439T - 0.000035PC + 0.000000PT + 0.000261CT - 0.005191P^2 - 2.84091\text{E-}06C^2 - 0.010955T^2$
	PC	Floatability (%) $= 86.21642 - 0.141963P - 0.054963\ C - 0.657488T - 3.21782\text{E-}06PC + 0.000000PT + 0.000080CT + 0.000135P^2 + 0.000013C^2 + 0.004218T^2$
	ABS	Floatability (%) $= 95.91642 + 0.086277P - 0.041801\ C - 0.781427T - 0.000172PC + 0.000000PT - 0.000078CT - 0.001067P^2 + 0.000014C^2 + 0.006759T^2$
PVA	POM	Floatability (%) $= 70.79661 - 0.280136P + 0.010507\ C - 0.783006T - 0.000121PC + 0.000000PT - 0.000160CT + 0.003051P^2 - 1.72484\text{E-}06C^2 + 0.011086T^2$
	PC	Floatability (%) $= 71.77381 - 0.394048P - 0.060455\ C - 0.685417T - 0.000021PC + 0.000000PT - 0.000064CT + 0.003125P^2 + 0.000022C^2 + 0.009449T^2$
	ABS	Floatability (%) $= 112.46667 - 0.662113P - 0.063100\ C - 1.41492T - 0.000102PC + 0.000000PT - 0.000036CT + 0.005492P^2 + 0.000026C^2 + 0.018281T^2$
PEG	POM	Floatability (%) $= 71.74922 - 0.088863P + 0.034020\ C - 0.636943T - 0.000131PC + 0.000000PT + 0.000034CT + 0.002018P^2 - 0.000011C^2 + 0.005981T^2$
	PC	Floatability (%) $= 81.19930 - 0.174209P + 0.020837\ C - 0.567562T - 0.000079PC + 0.000000PT + 0.000113CT + 0.001992P^2 - 8.16761\text{E-}06C^2 + 0.004258T^2$
	ABS	Floatability (%) $= 93.86398 - 0.208646P + 0.012047\ C - 0.402113T - 0.000044PC + 0.000000PT - 0.000086CT + 0.002181P^2 - 5.12378\text{E-}06C^2 + 0.005706T^2$
MC	POM	Floatability (%) $= 69.83481 - 0.021291P + 0.005175\ C - 0.197834T + 0.000048PC + 0.000000PT + 0.000220CT + 0.000120P^2 - 3.50041\text{E-}06C^2 - 0.000269T^2$
	PC	Floatability (%) $= 72.66612 - 0.031494P + 0.005603\ C - 0.199393T + 0.000052PC + 0.000000PT + 0.000220CT + 0.000306P^2 - 4.76867\text{E-}06C^2 + 0.000401T^2$
	ABS	Floatability (%) $= 87.11233 + 0.028370P - 0.023114\ C - 0.175527T + 0.000013PC + 0.000000PT + 0.000166CT + 0.000140P^2 + 6.29058\text{E-}06C^2 - 0.000624T^2$

then the entropy change will be positive and in case of the remaining other two parameters (ΔH_{ad} and T) un-changed, the sign of ΔG_{ad} will be negative. It seemed microwave irradiation was effective on the entropy of the system in different ways depending on the nature of the plastic surface. The authors concluded that several important parameters, including microwave irradiation strength and rate of irradiation, along with a complicated phenomenon involve in the flotation of the selected plastics. Table 2 represents the suggested equations by a design of experiment software (Design-Expert® statistical software) for the floatation % of studied plastics versus microwave power % (P), used depressant concentration (C, mg/L), and microwave irradiation time (T, second). The design of experiments (DOE) is a suitable technique to predict a desired property, i.e., floatation %) as output, with changing the above-mentioned selected input parameters. The response surface methodology (RSM) with D-Optimal method used to process the data. The predicted values were in good conformity with the experimental values. As an illustration, Fig. 10 compares the predicted values versus actual experimental values for conditioned PC with TA. As observed, the predicted floatation % values were close to actual values.

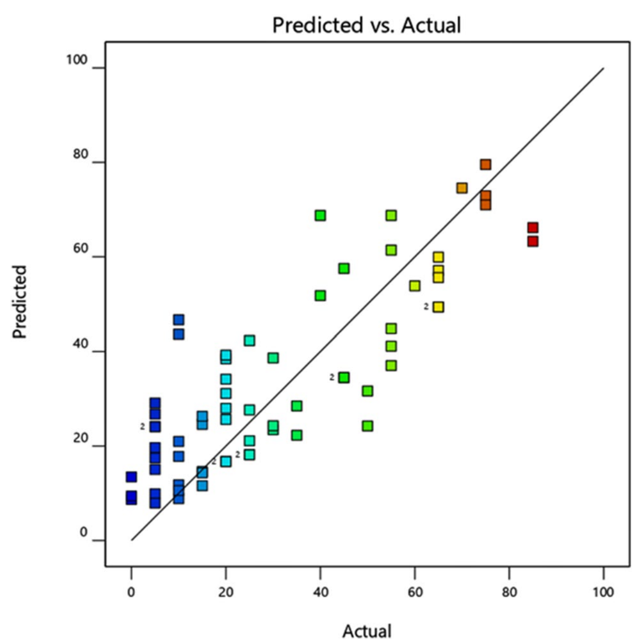


Fig. 10 The predicted values versus actual experimental values for conditioned PC with TA

Concluding remarks

The pre-microwave irradiation of the plastic surface was influential on the float-sink behavior of the studied plastics. The microwave irradiation was effective on the numbers, capacity (mono or multilayer adsorbed depressant molecule), and concentration of the active sites. The microwave irradiation reduced θ (contact angle) values of the un-conditioned plastic surface with studied depressants for all used plastics resulted in increasing the hydrophilic property of the surface of the plastics. However, for the description of depressant adsorption on a plastic surface, the reader should have a deep understanding of the adsorption–desorption process. The microwave pre-irradiation for some plastics and depressants was beneficial for plastic flotation whenever for other samples, it helped the plastic to sink at the bottom of the flotation tank. The suggested equations by Design-Expert® software to predict the plastic flotation % versus studied parameters conformed the experimental results appropriately.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10924-021-02105-6.

Acknowledgements The authors sincerely thank the staff of the polymer chemistry laboratory located at the faculty of science, the Ferdowsi University of Mashhad, for their sincere cooperation. Approval no. 3/51149.

Declarations

Conflict of interest The authors declare that they have not any financial/commercial conflicts of interest.

References

1. Chong-quine Wang H (2015) Wang. J Gang Fu, You-nian Liu, Flotation separation of waste plastics for recycling-A review, Waste Manag 41:28–38
2. Gu F, Guo J, Zhang W, Summers PA, Hall P (2017) From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Sci Total Environ 601–602:1192–1207
3. Davari MR, Ostad Movahed S (2019) The Flotation by Selected Depressants as an Efficient Technique for Separation of a Mixed Acrylonitrile Butadiene Styrene, Polycarbonate and Polyoxymethyleneplastics in waste streams. J. Polym. Environ. 27:1709–1720
4. Negari MS, Ostad Movahed S, Ahmadpour A (2018) Separation of polyvinylchloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET) granules using various chemical agents by flotation technique. Sep. Purif. Technol. 194:368–376
5. Gent R, Malcolm Menendez M, Toraño J, Torno S (2011) Optimization of the recovery of plastics for recycling by density media separation cyclones. Resour. Conserv. Recycl 55:472–482
6. Lee JJS, Mo JPT, Wu DY (2012) Polymer recovery from auto shredder residue by projectile separation method. Sustainability-Basel 4:643–655
7. Gent M (2009) Recycling of plastic waste by density separation: Prospects for optimization. Waste Manage Res 27:175–187
8. Pappa G et al (2001) The selective dissolution/precipitation technique for polymer recycling: a pilot unit application. Resour Conserv Recycl 34:33–44
9. Weeden GS, Soepriatna NH, Wang NL (2015) Method for efficient recovery of high-purity polycarbonates from electronic waste. Environ Sci Technol 49:2425–2433
10. Zhao Y, Lv X, Yang W, Ni H (2017) Laboratory simulations of the mixed solvent extraction recovery of dominate polymers in electronic waste. Waste Manage 69:393–399
11. Wu G, Li J, Xu Z (2013) Triboelectrostatic separation for granular plastic waste recycling: A review. Waste Manage 33:585–597
12. Silveira AVM, Cella M, Tanabe EH, Bertuol DA (2018) Application of triboelectrostatic separation in the recycling of plastic wastes. Process Saf Environ 114:219–228
13. Li J, Wu G, Xu Z (2015) Tribo-charging properties of waste plastic granules in process of tribo-electrostatic separation. Waste Manage 35:36–41
14. Gu GH, Hu YH, Qiu GZ, Wang H, Wang DZ (2002) Potential control flotation of galena in strong alkaline media. J Cent South Univ Technol 9:16–20
15. G. Deiringer, G. Edelmann, B. Rauxloh, U.S.Patent,5248041(1993).
16. Burat F, Güney A, OlgaçKangal M (2009) Selective separation of virgin and postconsumer polymers (PET and PVC) by flotation method. Waste Manage 29:1807–1813
17. Takoungsakdakun T, Pongstabodee S (2007) Separation of mixed post-consumer PET–POM–PVC plastic waste using selective flotation. Sep Purif Technol 54:248–252
18. Kangal MO (2010) Selective flotation technique for separation of PET and HDPE used in drinking water bottles. Min Proc Ext Met Rev 31:214–223
19. Basařová P, Bartovská L, Kořínek K, Horn D (2005) The influence of flotation agent concentration on the wettability and flotability of polystyrene. J Colloid Interf Sci 286:333–338
20. Guo J, Li X, Guo Y, Ruan J, Qiao Q, Zhang J, Bi Y, Li F (2016) Research on flotation technique of separating pet from plastic packaging wastes. Procedia Environmental Sciences 31:178–184
21. Yenial U, Burat F (2013) Separation of PET and PVC by Flotation Technique Without Using Alkaline Treatment. Min. Proc. Ext. Met. Rev. 34(6):412–421
22. Güney A, Özdilek C, Kangal MO, Burat F (2015) Flotation characterization of PET and PVC in the presence of different plasticizers. Sep Purif Technol 151:47–56
23. Yuce AE, Kilic M (2015) separation of PVC/PET mixture from plastic wastes using column flotation technique. J Environ Prot Ecol 16:705–715
24. Pascoe RD (2005) The use of selective depressants for the separation of ABS and 65 HIPS by froth flotation. Miner Eng 18:233–237
25. Motasemi F, Afzal MT (2013) A review on the microwave-assisted pyrolysis technique. Renew Sustain Energy Rev 28:317–330
26. Mollanorouzi M (2016) Saeed Ostad Movahed, Reclaiming waste tire rubber by an irradiation technique. Polym Degrad Stab 128:115–125
27. Movahed SO, Ansarifar A, Zohouri GH, Ghanei R, Kermani Y (2016) Devulcanization of ethylene–propylene–diene waste rubber by microwaves and chemical agents. J. Elastom. Plast. 48:122–144

28. Khavarnia M (2016) Saeed Ostad Movahed, Butyl rubber reclamation by combined microwave radiation and chemical reagents. J Appl Polym Sci 133:43363–43373
29. Srinivasa Reddy Mallampati (2018) Chi-Hyeon Lee, Min Hee Park, Byeong-Kyu Lee, Processinplastics from ASR/ESR waste: separation of poly vinyl chloride (PVC) by froth flotation aftemicrowave-assisted surface modification. J Mater Cycles Waste Manag 20:91–99
30. Gan Cheng; Ziyou Li (2020) Yijun Cao, Zhendong Jiang, Research progress in lignite flotation intensification. International Journal of Coal Preparation and Utilization 40:59–76
31. Truc NTT, Lee B-K (2017) Combining ZnO/microwave treatment for changing wettability of WEEE styrene plastics (ABS and HIPS) and their selective separation by froth flotation. Appl Surf Sci 420:746–752
32. Srinivasa Reddy Mallampati (2018) Chi-Hyeon Lee, Min Hee Park, Byeong-Kyu Lee, Processing plastics from ASR/ESR waste: separation of poly vinyl chloride (PVC) by froth flotation after microwave-assisted surface modification. J Mater Cycles Waste Manag 20:91–99
33. Irannajad M, Mehdilo A (2014) Omid Salmani Nuri, Influence of microwave irradiation on ilmenite flotation behavior in the presence of different gangue minerals. Sep Purif Technol 132:401–412
34. Huang L, Wang H, Wang C, Zhao J, Zhang Bo (2017) Microwave-assisted surface modification for the separation of polycarbonate from poly methyl methacrylate and polyvinyl chloride waste plastics by flotation. Waste Manag Res 35:294–300
35. Zhang Y, Jiang H, Wang H, Wang C, Yichen Du, Wang L (2020) Flotation separation of polystyrene and polyvinyl chloride based on heterogeneous catalytic Fenton and green synthesis of nanoscale zero valent iron (GnZVI). J Clean Prod 267:122116
36. Zhang Y, Jiang H, HuiWang ChongqingWang (2020) Flotation separation of acrylonitrile-butadiene-styrene and polystyrene in WEEE based on oxidation of active sites. Miner. Eng. 146:106131
37. Zhang Y, Jiang H, Wang H (2020) Separation of hazardous polyvinyl chloride from waste plastics by flotation assisted with surface modification of ammonium persulfate: Process and mechanism. J. Hazard. Mater. 389:121918
38. Zhang Y, Jiang H, Wang K, Wang H, ChongqingWang, (2020) Green flotation of polyethylene terephthalate and polyvinyl chloride assisted by surface modification of selective $CaCO_3$ coating,). J. Clean. Prod. 242:118441
39. HuiWang YingshuangZhang (2019) Chonqing Wang, Surface modification and selective flotation of waste plastics for effective recycling- a review. Sep Purif Technol 226:75–94
40. Shen H, Forssberg E, Pugh RJ (2002) Selective flotation separation of plastics by chemical conditioning with methyl cellulose. Resour Conserv Recycl 35:229–241
41. Aumann T, Theirich D, Engemann J (2001) Rapid surface modification of polyethylene in microwave and rf-plasmas: comparative study. Surf. Coat. Technol. 142–144:169–174
42. Zhao Q (2014) ShengZhang, Mingzhe Dong, Peng Jiang, Zhongwu Hu, Surface modification of polyamide 66 fabric by microwave induced grafting with 2-hydroxyethyl methacrylate. Surf Coat Technol 240:197–203
43. Saleh NS, Ostad Movahed S (2018) Attarbashi, Study on the antibiofouling effects of the grafted polyamide 6 fibers by several vinyl chemicals. J. Appl. Polym. Sci. 135:46760–46770
44. Ginn BT, Steinbock O (2003) Polymer Surface Modification Using Microwave-Oven-Generated Plasma. Langmuir 19:8117–8118
45. Masel IR (1996) Principles of adsorption and reaction on solid surfaces. Wiley, New York
46. Gregg GC, Sing KSW (1982) Adsorption, surface area and porosity, 2nd edn. Academic, London
47. Zhao Y, Yang S, Wen H, Shen Z, Han F (2019) Adsorption behavior and selectivity mechanism of flotation reagents applied in ternary plastic mixtures. Waste Manage 87:565–576