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ORIGINAL ARTICLE

Separation of plastic mixtures by sink-float combined with froth flotation

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Abstract

The aim of this research was to separate a mixture of six post-consumer plastics (PS, PMMA, PVC-D, PVC-M, PET-D and PET-S) by combination of sink-float separation and froth flotation.. In sink-float method two mediums of separation were used: sodium chloride water solution and ammonium nitrate water solution. Sink-float method allowed complete separation of the less dense plastic (PS) from intermediate density plastics (PMMA and PVC-D) and from high density plastics (PET-S, PET-D and PVC-M); also allowed good separation of intermediate density plastics (PMMA and PVC-D) from high density plastics (PVC-M, PET-D and PET-S) with an efficiency close to 100%. Separation of PVC-M from PET-D and PET-S by sink-float method led to fair results allowing a separation efficiency of about 60%. Since PMMA and PVC-D have similar density, their separation was achieved by froth flotation, using sodium lignosulfonate as selective wetting agent of PVC-D, with a separation efficiency of 85%.

Keywords: *density separation, plastic, mixture, particle size.*

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1. Introduction

The management of urban solid waste (MSW) is one of the major environmental concerns worldwide. Its production has increased continuously, reaching in 2020 a world production of 2.24 billion tons, which corresponds to a per capita production of 0.79 kg/person.day. At worldwide, plastics are one of the main constituents of MSW, representing about 12% of its weight[1]. Due to the low price of plastics and their excellent properties that give them multiple applications, the world production of plastics has increased continuously, reaching 367 million tons in 2020, which is a contrasting value with the approximately 5 million tons produced in the 50s of the last century[2].

Despite the constant increase in their consumption, in recent years plastics have acquired a negative reputation, with strong public pressure on their use. Regarding the management of plastic waste, it can be landfilled, incinerated with energy production or recycled. In view of the non-biodegradability of most plastics, they cause the difficulties in the degradation of fermentable materials placed in landfills, and their incineration generates toxic gases. Thus, the most environmentally and economically correct solution is to proceed with recycling, in which plastics should not be seen as a waste, but rather as a resource[3].

Despite the importance of recycling, the vast majority of plastic waste ends up in landfills or the natural environment, or are incinerated, causing serious environmental problems. In 2019, only about 9% of world plastic waste was recycled, while 19% was incinerated, almost 50% went to sanitary landfills, and the remaining 22% was disposed of in uncontrolled dumpsites, burned in open pits or leaked into the environment[4]. Plastic waste management vary by country income level. In low-income countries the recovery rate of plastic waste is lower, with most of it being mismanaged or uncollected. In Europe Union, during 2020, 34.6% of plastic waste was recycled, 42% was recovered through energy recovery processes and 23.4% was landfilled[2]. In Africa nearly 60% of plastic waste was mismanaged or littered, around 5% was recycled and the rest was deposited in landfills[4].

Thus, it is urgent to substantially reduce the use of plastics, and reduce the deposition in landfills or in dumps through recycling. However, in order to recycle plastic waste it is necessary to separate the plastic mixtures into individual plastics because different plastics cannot be recycled together due to chemical incompatibilities, different melting points and thermal stabilities, and therefore cannot be mixed in the recycling process[5]. However, separating plastics is not easy because there are many types and most of them have similar properties. In recent years several methods were developed for plastics separation. These methods include automatic separation based on surface properties: X-ray detection[6]; infrared spectroscopy[7] and optical separation based on color[7]. These methods can only be applied when the plastics are clean and of significant size, larger than 30 mm, as the quality of separation significantly deteriorates with decreasing particle size and surface contamination[7,8]. Other methods to separate plastic are as follows:

- Electrostatic separation, which is based on the difference in electrical conductivity of plastics[9].

- Froth flotation separation, the most important method of separation in mineral processing, which is based on the different degree of particles hydrophobicity. It is a physicochemical process that is based on the selective adhesion of particles to air bubbles (hydrophobic particles) or to water (hydrophilic particles)[10-15].

- Selective solvent dissolution methods[16] that usually involve temperature variations because the solubility of a polymer in a given solvent changes with this variable. The toxic organic solvents associated with high costs makes alternative methods more attractive.

- Gravity separation methods (density separation), which are based on the difference in plastics density, and can be performed in different equipment, such as jigs, shaking table, liquid fluidized bed techniques and cylindrical cyclone media separator[17,18]. Some means have been used to separate plastics, such as water, saturated water solutions with sodium chloride, calcium chloride and ethanol solutions[19,20].

Several combination techniques are also used for the separation of mixed plastic, like air tabling and triboelectric techniques[21]; sink-float separation and flotation[22]; or jigging and flotation[23].

In density separation (sink-float) the plastics with different density are placed in a liquid of intermediate density, where the denser plastics sink and separates out from the less dense floating plastics. The separation efficiency depends on the medium's density which lies between the different densities of the plastics. A sink-float separation is efficient when plastics have significantly different density. When plastics have a low density difference, separation may be hard or even impossible. Sometimes air bubbles adhere to the surface of plastics and alter the float and sink features of plastic particles[20].

To obtain water solutions with different density several products have been used, such as: ethanol to obtain solutions with density lower than 1 g/cm^3, and sodium chloride which allows obtaining water solutions with density up to 1.2 g/cm^3[20]. To obtain water solutions with a higher density have been used sodium polytungstate, zinc chloride calcium chloride, sodium iodine and lithium metatungstate[22,24,25,26]. However, these higher density solutions are toxic to the environment and often very expensive, limiting their use[26]. On the other hand, sodium chloride it is environmentally benign, cheaper and widely available[26].

This work aimed to study the separation of post-consumer plastic mixture by sink-float (density separation) combined with froth flotation separation. Froth flotation was used when sink-float performance was poor. For the density separation two mediums separation are used: sodium chloride water solution and ammonium nitrate water solution. For the separation of plastic mixtures by froth flotation, sodium lignosulfonate was used as a wetting agent. The effect of the solution density and the effect of particle size and particle hydrophobicity on the density separation performance was analysed.

2. Materials and Methods

2.1 Materials

This study used six types of granulated plastics from three recycling companies: Polystyrene (PS), Polymethyl methacrylate (PMMA), Polyethylene Terephthalate (PET-D) and Polyvinyl Chloride (PVC-D) from Daniel Morais, Polyethylene Terephthalate (PET-S) from Selenis, and Polyvinyl Chloride (PVC-M) from Micronipol (Figure 1). The plastics differed on colour and shape, which facilitated separation through manual sorting at the end of each separation test. The density of these plastics was determined in our previous work[18], represents the average of three samples, ranged from 1.047 g/cm^3 (PS) to 1.372 g/cm^3 (PET-S) (Table 1).

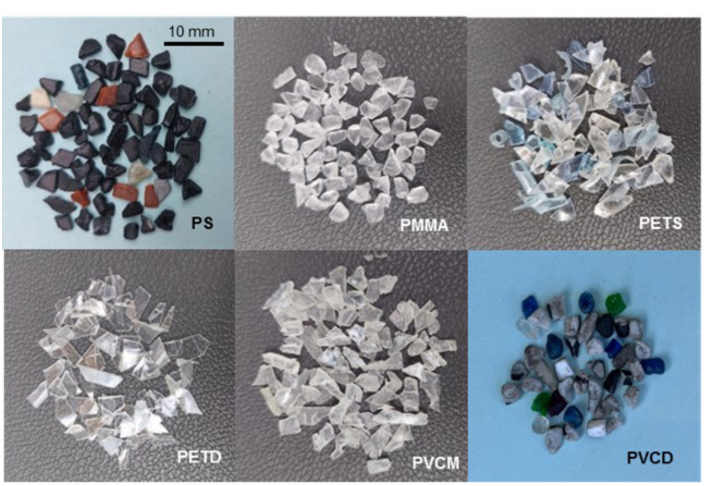

Figure 1. Photographs of the studied plastic samples.

Table 1. Density and characteristics of the studied plastics.

Types of plastic	Density (g/cm^3)	Characteristics
PS	1.047±0.003	dark colored, irregular
PMMA	1.204±0.003	colorless to white, transparent, irregular
PET-S	1.372±0.007	blue colored, traslucid, lamellar)
PET-D	1.364±0.004	colorless, transparent, lamellar
PVC-M	1.326±0.005	light green to white, translucid, lamellar
PVC-D	1.209±0.006	gray colored, irregular

According to the density of plastics it is possible to separate the six plastics into three groups: the first group constituted only by the PS, that has a less density, a second group that includes PMMA and PVC-D that have intermediate density, and the third group that includes PVC-M, PET-S and PET-D that have high density. So, it is expected that the sink-float method is appropriate to individually separate PS from the others five plastics, and also is suitable to separate PMMA and PVC-D from PET-S, PET-D and PVC-M; in addition, it is not suitable to separate PMMA from PVC-D as they have similar density. It is also expected that it will be difficult to separate PVC-M from PET-S and PET-D because of the slight difference in their density.

Particles size has an important role in separation processes. To study the influence of the particles size in the sink-float separation and in the froth flotation separation, two size fractions of the six plastics were used: +1.4-2.0 mm and +2.8-4.0 mm.

2.2 Density separation experiments

To obtain dense solutions, sodium chloride and ammonium nitrate are used because they are cheap, widely available and have a low environmental impact than other products that can also be used to obtain dense solutions, such as sodium polytungstate, zinc chloride, sodium iodine, lithium metatungstate[26]. Also other studies have used sodium chloride[20,26]. Sink-float separation of plastics using sodium chloride water solution and ammonium nitrate water solution with various densities was tested. For this, different amounts of sodium chloride and ammonium nitrate were mixed into water on a mechanical stirrer. The maximum density obtained for the sodium chloride solution was 1.203 g/cm^3, and the maximum density obtained for the ammonium nitrate solution was 1.380 g/cm^3. Sink-float tests were performed in a glass beaker with a capacity of 1 dm^3, and in each test 10 g of plastics were used. Prior to the density separation test, the plastics were mixed with tap water in a stirrer during 5 minutes so that the plastics were completely moistened avoiding air bubble formation. Subsequently, the plastics were left in the separation medium. Plastics with a lower density than separation medium floated to the surface while the plastics with a higher density than separation medium sank to the bottom. The separation tests were carried out for 2 minutes (waiting time required for the particles to fall into the solution). After 2 minutes, the floated and sunk products were manually collected and then washed with tap water, dried and weighed to evaluate their recovery based on mass balance.

First, tests were carried out with one-component plastic samples in solutions with different densities. Then, density separation of binary plastic mixtures was performed using several bi-component mixtures, contributing each plastic with 50% of the weight in solutions with different densities.

2.3 Froth flotation separation experiments

Froth flotation tests were performed in a Denver cell with a capacity of 3 dm^3. Each test used 40 g of PMMA/PVC-D mixture, in equal proportions, and was conditioned with sodium lignosulfonate for about 5 minutes and later with frother (Methyl isobutyl carbinol - MIBC) for about 2 minutes before the flotation, at the constant concentration of 30x10^{-3} g/L in all experiments. After conditioning, floated product was collected over 6 minutes.

After the experiments of density separation and froth flotation, the floated and sunk products were dried and weighed. The control of the separation of binary plastic mixtures was carried out using the recovery and grade of each type of plastic in the floated and in the sunken products, after manual sorting and weighing of the two types of plastics. This was possible due to the different colours and shapes of the plastics particles. The tests were carried out three times under similar operating conditions, and the values represent the mean value of independent experiments. The effectiveness of the plastic separation was quantified by the efficiency of separation, defined by Schulz[27]: $\eta = R_{P1} - R_{P2}$ (where η is the separation efficiency, R_{P1} is the recovery of plastic 1 in the floated and R_{P2} is the recovery of plastic 2 in the floated).

3. Results and Discussion

3.1 One-component plastic

Figure 2 shows the effects of density of sodium chloride water solution on the recovery in the floated of six plastics for two size fractions: +1.4-2.0 mm and +2.8-4.0 mm. For the two size fractions the recovery in the floated of the six plastics increased with the increasing of medium density. Although the two size fractions show similar results, the coarse fraction (+2.8-4.0 mm) led to slightly lower floated recovery.

When only tap water was used (density = 1.0 g/cm^3) some PS and some PVC-D floated. Under these conditions the other four plastics sank completely. PS plastic had a greater increase of floatability when increase the medium density in comparison with the other five plastics. It was observed that for a medium density greater than 1.05 g/cm^3 all PS floated and for a medium density greater than 1.200 g/cm^3 all PMMA floated.

For PS and PMMA the recovery in the float increases sharply with the variation of medium density, but for PVC-D floated recovery increases gradually with the variation of medium density. For the range of densities evaluated, the floated recovery of the three densest plastics (PET-S, PET-D and PVC-M) is very small because these plastics have a density clearly higher than the maximum density of the medium (1.203 g/cm^3).

The use of ammonium nitrate solution allowed obtaining a medium with higher density, reaching a maximum density of 1.380 g/cm^3. Thus, this solution allowed a better evaluation of the behavior of denser plastics (PET-S, PET-S and PVC-M) than the sodium chloride solution. For the six plastics and for the two size fractions the floated recovery increased with the increasing of density of ammonium nitrate water solution (Figure 3). For a density of 1.38 g/cm^3, the floated recovery of the six plastics was 100%. PET-D is the plastic with the lowest floated recovery. In this solution, the behavior of PS, PMMA and PVC-D is similar to that observed for the sodium chloride solution. However, recovery in floated of these three plastics is slightly lower when using ammonium nitrate solution. Although the plastics have been previously washed, it is likely that the formation of some air microbubbles attached to the plastics particles when sodium chloride was used are responsible for the highest floated recovery in this solution.

On the two separation medium, for the six plastics, the fine fraction (+1.4-2.0 mm) showed greater floated recovery than the coarse fraction (+2.8-4.0 mm). This means that large particles sink more easily into the medium than fine particles. For example, for PVC-D in sodium chloride solution, when medium density is 1.180 g/cm^3, floated recovery was 36.2% for fraction +1.4-2.0 mm and was 25.4% for fraction +2.8-4.0 mm. For PVC-D in ammonium nitrate solution, when medium density is 1.180 g/cm^3, floated recovery was 32.2% for fraction +1.4-2.0 mm and was 22.5% for fraction +2.8-4.0 mm. Since the density of plastics is independent of particle size, the higher floated recovery of the fine fraction may result from the possibility that some air microbubbles attached to the particles and make it difficult for them to sink, being this effect more pronounced for the finer particles because they weigh less (being easier to get particle-bubble aggregates with density lower than the density of medium).

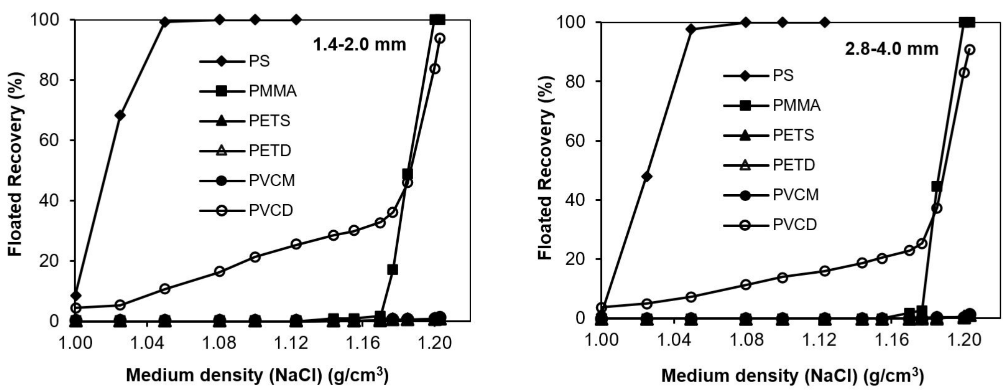

Figure 2. Influence of density of sodium chloride solution on floated recovery of six plastics for fractions +1.4-2.0 mm and +2.8-4.0 mm.

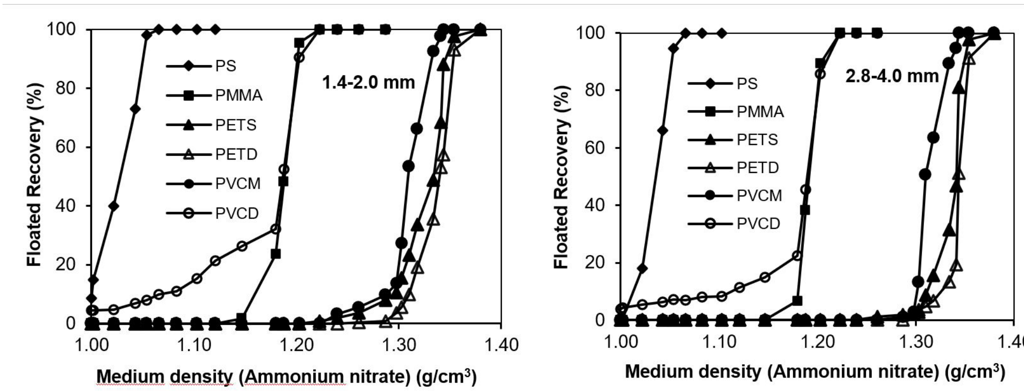

Figure 3. Influence of density of ammonium nitrate water solution on floated recovery of six plastics for fractions +1.4-2.0 mm and +2.8-4.0 mm.

PMMA and PET-D plastics are the ones more homogeneous, with particles of similar texture, similar shape and the same appearance (color). The other plastics have a less homogeneous texture, with particles of different shape and different appearance (color). For example, for PET-S, particles from the body of a bottle and its neck are visible, these having a different texture. This may mean that in each type of plastic, particularly in less homogeneous ones, there are particles with slightly different density, and so the floated recovery variation is more gradual, occurring in a larger range of density of the medium. This behavior is more evident for PVC-D. On the other hand, the drastic variation of floated recovery *versus* density of medium is fundamentally observed for homogeneous plastics, such as PMAA and PET-D.

The density of the six plastics has the following order: PS < PMMA ≈ PVC-D < PVC-M < PET-D ≈ PET-S. In the two dense medium, and for the two size fractions, the floated recovery of the six plastics follows the order: PS > PVC-D > PMMA > PVC-M > PET-S > PET-D. The order of flotation is slightly different from the order of density. Although PET-D is not the densest plastic, it is the one with the least flotation. Also, although PVC-D has a density similar to PMMA, it has greater flotation than that plastic, particularly for medium density less than 1.18 g/cm^3.

Although the separation of plastics in dense medium mainly depends on their density, other physical properties of particles such as size, shape, texture and hydrophobicity grade also influence the behavior of plastics in a medium. Although the plastics have been previously washed in order to avoid the formation of air bubbles, during the separation tests there is the possibility of air microbubbles attach to the plastic particles, which may affect the results. The possibility of attaching air microbubbles to plastic particles depends on the hydrophobicity grade of the plastics. In the plastics that are more hydrophobic, i.e. with a higher contact angle, the probability of attachment of the air microbubbles to their surface is greater[10]. Contact angle indicates the degree of wetting when a solid and a liquid interact. If the contact angle is very small, then the air bubbles do not attach to the particle surface, while a very large contact angle results in a very strong bubble attachment to the particle. Previous study[14] showed that these six plastics are naturally hydrophobic, and that the contact angle of the six plastics is as follows: PS - 97º, PMMA - 77º, PET-S - 85º, PET-D - 73º, PVC-M - 85º, and PVC-D - 92º[14]. Thus, since PMMA and PVC-D have similar density, the greater floated recovery of PVC-D than PMMA, may be a consequence of its higher contact angle, as the probability of attachment of air microbubbles is greater. Also PET-S and PET-D have similar density and therefore, the greater recovery in sunk of PET-D may be a consequence of its lower contact angle, thus being less likely for air microbubbles to attached to the PET-D particles, sinking them more easily than PET-S.

If air microbubbles attach to the plastic particles, they can float in medium with a density lower than the density of plastics. For example, for PMMA, whose density is 1,204 g/cm^3, for fraction +1.4-2.0 mm, when density of sodium chloride solution is 1,185 g/cm^3, the floated recovery was 48.8%. It was expected that the floated recovery would be none, that is, the entire PMMA would sink, as the medium density is lower than plastic density. These behavior is a result of air microbubbles attaching to plastic particles.

The shape of the particles does not seem to influence their behavior in the dense medium. It would be expected that particles with a more lamellar shape might have a greater tendency to float. The plastic with more lamellar shaped particles is PET-D, however it was the one with the highest recovery in the sunken.

3.2 Separation of bi-component mixtures of plastics by sink-float

3.2.1 Mixtures of PS with other plastics

According to the floated recovery of plastics, it is possible to separate the six plastics into three groups: the first group constituted only by PS, that has the highest floated recovery (low density); a second group that includes PMMA and PVC-D that have intermediate floatability (intermediate density), and the third group that includes PVC-M, PET-S and PET-D that have lowest floatability (high density).

In face of these results, further separation tests were developed using bi-component plastic mixtures of PS and other plastic, in equal proportions, for two size fractions (+1.4-2.0 mm and +2.8-4.0 mm), with the intention to obtain a sunk without PS and a floated of PS. For the separation of PS/PMMA and PS/PVC-D mixture was used sodium chloride water solution with a density of 1.08 g/cm^3, and for the separation of PS/PET-S, PS/PET-D and PS/PVC-M mixtures was used sodium chloride water solution with a density of 1.12 g/cm^3. Thus, these densities led to the most efficiente separation of bi-component plastic mixtures of PS and other plastic. For that range of densities, ammonium nitrate solution could also have been used. It was decided to use the sodium chloride solution because it is cheaper and it has a low environmental impact[26].

It can be stated that sink-floatseparation of PS from PMMA, PET-S, PET-D or PVC-M was efficient (Table 2). For these four mixtures the separation efficiency was perfect (100%), since all the PS floated and all the other plastics sunk. The influence of the particles size in the separation quality of the four mixtures is not evident.

On the other side, PS/PVC-D had the worst separation efficiency, with separation efficiency close to 85%, because about 15% of PVC-D plastic was recovered in the floated. These results were consistent with the floatability of plastics observed in the mono-component tests (Figures 2 and 3). The separation of PS/PVC-D mixture presented best results for the coarse size fraction (+2.8-4.0 mm) because PVC-D recovery in the floated decreased with the increase in particle size.

3.2.2 Mixtures of PMMA with other plastics

In order to separate PMMA from PET-S, PET-D and PVC-M mixtures into individual polymers, an ammonium nitrate water solution with density of 1.23 g/cm^3 was used (Table 3). This was the density that allowed the greatest separation efficiency of those three plastic mixtures. In this separation, sodium chloride solution was not used because it does not allow obtaining a density greater than 1.203 g/cm^3.

For the three mixtures all the PMMA floated because its density is lower than the density of the medium. The two size fractions of PET-D and coarser fraction of PET-S and PVC-M completely sink. So, for these mixtures, the separation was perfect, with a separation efficiency of 100%, resulting in a pure sunk and a pure floated.

Although the PMMA/PET-S and PMMA/PVC-M mixtures have led to lesser results for the fine fraction (+1.4-2.0 mm), the separation efficiency is high (about 98%).

3.2.3 Mixtures of PVC-D with other plastics

To separate PVC-D from PET-S, PET-D and PVC-M mixtures into individual polymers, also an ammonium nitrate water solution with density of 1.23 g/cm^3 was used. The separation of the three mixtures had similar results (Table 4). These mixtures present similar results to the mixtures of PMMA with the other three plastics. For all mixtures the floated recovery of PVC-D was 100%. The two size fractions of PET-D and coarser fraction of PET-S and PVC-M completely sank.

Table 2. Recovery and grade of the floated (concentrated of PS) and sunk products, in the separation of bi-component mixtures of PS with other plastics by sodium chloride water solution.

Mixture	Size fraction (mm)	Floated (overflow)		Sunk (underflow)	
		Grade (%)	PS	PMMA	PMMA
			Recovery (%)	Grade (%)	Recovery (%)
PS/PMMA	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PS	PS	PET-S	PET-S
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PS/PET-S	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PS	PS	PET-D	PET-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PS/PET-D	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PS	PS	PVC-M	PVC-M
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PS/PVC-M	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PS	PS	PVC-D	PVC-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PS/PVC-D	+1.4-2.0	85.8	100	100	83.5
	+2.8-4.0	89.6	100	100	88.4

Table 3. Recovery and grade of the floated and sunk products, in the separation of bi-component mixtures of PMMA with PET-S, PET-D and PVC-M by ammonium nitrate water solution.

Mixture	Size fraction (mm)	Floated (overflow)		Sunk (underflow)	
		PMMA	PMMA	PET-S	PET-S
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PMMA/PET-S	+1.4-2.0	98.5	100	100	98.5
	+2.8-4.0	100	100	100	100.0
		PMMA	PMMA	PET-D	PET-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PMMA/PET-D	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PMMA	PMMA	PVC-M	PVC-M
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PMMA/PVC-M	+1.4-2.0	97.7	100	100	97.6
	+2.8-4	100	100	100	100

For these mixtures, the separation was perfect, with a separation efficiency of 100%. PVC-D/PET-S and PVC-D/PVC-M mixtures have led to worst results for the fine fraction, but the separation efficiency is high (about 98%).

3.2.4 Mixtures of PVC-M with other plastics

In order to separate PVC-M from PET-S and PET-D mixtures into individual polymers an ammonium nitrate water solution with density of 1.33 g/cm^3 was used (Table 5). This density led to the most efficient separation of bi-component plastic mixtures of PVC-M/PET-S and PVC-M/PET-D. The optimal density of the medium should be only slightly higher than the density of the lighter plastic (PVC-M - 1.326 g/cm^3). Separation tests on medium with density of 1.34 and 1.35 g/cm^3 led to poorer quality separations. However, Fu et al.[19] observed the opposite, concluding that the optimum value of the medium's density lies near that of the denser particles.

For the two mixtures the quality of separation improved slightly with the increase of the particles size. While the PVC-M recovery in the floated had decreased slightly with the increase of the particles size, the PET-S and PET-D recovery in the sunk had increased significantly with the increase of the particles size and therefore, the best separations were achieved for coarse fraction (+2.8-4.0 mm). PVC-M/PET-D mixture with size +2.8-4.0 mm had the greatest separation efficiency (77.4%), having be obtained a floated with a grade of 88.8% in PVC-M and a sunk with a grade of 88.8% in PET-D. On the other side, size fraction of +1.4-2.0 mm of PVC-M/PET-S mixture had the lowest separation efficiency, of about 46%, with a PVC-M grade in the floated of 66.5% and a PET-S grade in the sunk of 87.7%.

In a gravity separation of two materials, the separation efficiency must be larger when the density difference is greater. Thus, based on plastics density (Table 1), it would be expected that the PVC-M/PET-S and PVC-M/PET-D mixtures had similar results because PET-S and PET-D have similar density. Surprisingly, PVC-M/PET-D mixture showed better results than PVC-M/PET-S mixture. Therefore, these results cannot be explained by the density difference. The best results for PVC-M/PET-D mixture could be explained by the lower contact angle of the PET-D, thus being less likely for air microbubbles to attached to the PET-D particles, sinking them more easily than PET-S.

3.2.5 Separation of PMMA/PVC-D mixture by froth flotation

Since PMMA and PVC-D have similar density, separation of the mixture of these two plastics was not possible by gravity method. So, to separate PMMA/PVC-D mixture, selective froth flotation tests had been carried out.

Table 4. Recovery and grade of the floated and sunk products, in the separation of bi-component mixtures of PVC-D with PET-S, PET-D and PVC-M by ammonium nitrate water solution.

Mixture	Size fraction (mm)	Floated (overflow)		Sunk (underflow)	
		PVC-D	**PVC-D**	**PET-S**	**PET-S**
		Grade (%)	**Recovery (%)**	**Grade (%)**	**Recovery (%)**
PVC-D/PET-S	+1.4-2.0	98.3	100	100	98.3
	+2.8-4.0	100	100	100	100
		PVC-D	PVC-D	PET-D	PET-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PVC-D/PET-D	+1.4-2.0	100	100	100	100
	+2.8-4.0	100	100	100	100
		PVC-D	PVC-D	PVC-M	PVC-M
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PVC-D/PVC-M	+1.4-2.0	97.6	100	100	97.5
	+2.8-4.0	100	100	100	100

Table 5. Recovery and grade of the floated and sunk products in the separation of bi-component mixtures of PVC-M with PET-S and PET-D by ammonium nitrate water solution.

Mixture	Size fraction (mm)	Floated (overflow)		Sunk (underflow)	
		PVC-M	**PVC-M**	**PET-S**	**PET-S**
		Grade (%)	**Recovery (%)**	**Grade (%)**	**Recovery (%)**
PVC-M/PET-S	+1.4-2.0	66.5	92.5	87.7	53.3
	+2.8-4.0	75.9	89.3	87.0	71.6
		PVC-M	PVC-M	PET-D	PET-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PVC-M/PET-D	+1.4-2.0	73.3	92.2	89.5	66.4
	+2.8-4.0	88.8	88.6	88.6	88.8

Table 6. Results of the flotation tests on the mixture of PMMA/PVC-D in the presence of sodium lignosulfonate.

Mixture	Size fraction (mm)	Floated (overflow)		Sunk (underflow)	
		PMMA	PMMA	PVC-D	PVC-D
		Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PMMA/PVC-D	+1.4-2.0	94.5	96.2	96.1	94.4
	+2.8-4.0	92.8	82.5	84.2	93.3

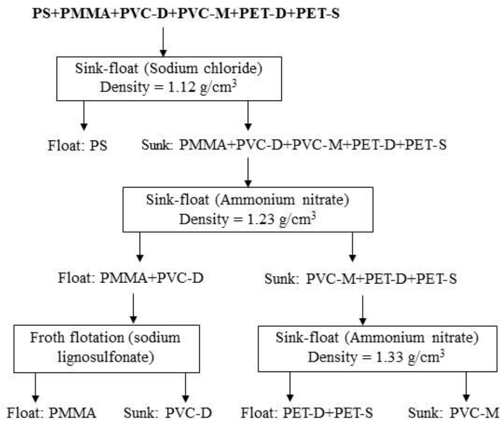

Figure 4. Flowchart of separation of plastic mixture (PS+PMMA+PVC-D+PVC-M+PET+D+PET-S) by sink-float and by froth flotation.

Plastics are naturally floatable in the absence of a wetting agent. Thus, in order to separate plastic mixtures by froth flotation, several wetting agents had been tested for the selective flotation of plastic mixtures[28-31]. Pita and Castilho[32] verified that floatability of PMMA and PVC-D decreases with an increase of the sodium lignosulfonate concentration. However, they also verified that in presence of this wetting agent, PVC-D has lower floatability than PMMA. So, in the presence of sodium lignosulfonate, flotation tests were developed using bi-component plastic mixtures of PMMA/PVC-D in equal proportions, to obtain a selective separation.

The ideal concentration of sodium lignosulfonate that led to the most efficient separation of PMMA/PVC-D mixture was selected from previous tests. It was verified that the concentration of 1000 mg/L led to the most efficient separation for the fine fraction (+1.4-2.0 mm), and the concentration of 80 mg/L led to the most efficient separation for the coarse fraction (+2.8-4.0 mm). The experimental results of these separation tests are presented in Table 6. The quality of the flotation separation of PMMA/PVC-D mixture was reasonable. The separation was more efficient for the fine fraction because there was a greater amount of PMMA recovered in the floated. For this fraction, the separation efficiency was 90.6%, having obtained a floated with a grade of 94.5% in PMMA and a sink with a grade of 96.1% in PVC-D. For the coarse fraction the separation efficiency was only 75.8%.

4. Conclusions

In this study the separation of mixed post-consumer plastic (PS, PMMA,VC-D, PVC-M, PET-D and PET-S) by combination of sink–float method and froth flotation was investigated. In sink-float method two mediums of separation were used: sodium chloride water solution and ammonium nitrate water solution. In froth flotation sodium lignosulfonate was used as selective wetting agent of PVC-D. The success of the sink-float separation of plastic mixtures depends on the density difference of the plastics and on the density of the separation medium. The application of the sink-float method does not require very different densities between the plastics of the mixture; even for plastic mixtures that have a small density difference, the sink-float method can lead to good quality separations. The optimal density of the medium should only be slightly higher than the density of the lighter plastic. The quality of separation also depends on the particles size and their hydrophobicity (contact angle).

In sink-float method floated recovery of the six plastics decrease with the increase of the medium density and decrease with the increase of particle size. In some mixtures, separation improved with increasing particle size. Separation is better when the floating plastic has a greater contact angle than the sinking plastic. The hydrophobicity of the particles influences plastic behavior in the sink-float method. The possibility of attaching air microbubbles to plastic particles during the separation depends on the hydrophobicity grade of the plastics, the attachment of air microbubbles is smaller for less hydrophobic plastics, that is, have a smaller contact angle, such as PET-D, which has the smallest contact angle among the studied plastics.

In face of the experimental results of the separation of plastic mixtures by sink-float and by froth flotation, it can be assumed that it is possible to separate the mixture of the six plastics (PS, PMMA, PVC-D, PVC-M, PET-D,PET-S) using density separation combined with froth flotation, obtaining almost clean products of PS, PMMA, PET and PVC. Figure 4 shows the sequence of separation operations to which the mixture of six plastics must be submitted and the respective products obtained.

For mixture of plastics that join a less density plastic (PS) with intermediate density plastics (PMMA and PVC-D) and with high density plastics (PVC-M, PET-D and PET-S), the separation efficiency of the sink-float method was close to 100%. Only some PVC-D floats together with the PS. Sink-float separation also allowed perfect separation of intermediate density plastics (PMMA and PVC-D) from high density plastics (PVC-M, PET-D and PET-S); all PMMA and PVC-D floats. Separation of PVC-M from PET-D and PET-S by sink-float method led to a reasonable quality of separation, since no clean products were obtained. The quality of separation improved slightly with the increase of the particles size.

Since it was not possible to separate successfully the PMMA/PVC-D mixture by sink-float method, this separation was carried out by froth flotation, which led to a separation efficiency of 90% for size fraction of +1.4.4-2 mm and of 76% for size fraction of +2.8-4 mm.

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6. References

1. Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. Washington, DC: World Bank. Urban Development Series. http://dx.doi.org/10.1596/978-1-4648-1329-0.
2. Plastics Europe. (2021). *Plastics - the facts 2021 - an analysis of European plastics production, demand and waste data*. Brussels: Plastics Europe/European Association of Plastics Recycling and Recovery Organisations. Retrieved in 2023, April 4, from https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf
3. Al-Salem, S. M., Lettieri, P., & Baeyens, J. (2009). Recycling and recovery routes of plastic solid waste (PSW): a review. *Waste Management*, *29*(10), 2625-2643. http://dx.doi.org/10.1016/j.wasman.2009.06.004. PMid:19577459.
4. Organisation for Economic Co-operation and Development – OECD. (2022). *Global plastics outlook: economic drivers, environmental impacts and policy options*. Paris: OECD Publishing. https://doi.org/10.1787/de747aef-en.
5. Yenial, Ü., Burat, F., Yüce, A. E., Güney, A., & Kangal, M. O. (2013). Separation of PET and PVC by flotation technique without using alkaline treatment. *Mineral Processing and Extractive Metallurgy Review*, *34*(6), 412-421. http://dx.doi.org/10.1080/08827508.2012.702705.
6. Gundupalli, S. P., Hait, S., & Thakur, A. (2017). A review on automated sorting of source-separated municipal solid waste for recycling. *Waste Management*, *60*, 56-74. http://dx.doi.org/10.1016/j.wasman.2016.09.015. PMid:27663707.
7. Zheng, Y., Bai, J., Xu, J., Li, X., & Zhang, Y. (2018). A discrimination model in waste plastics sorting using NIR hyperspectral imaging system. *Waste Management*, *72*, 87-98. http://dx.doi.org/10.1016/j.wasman.2017.10.015. PMid:29129466.
8. Masoumi, H., Safavi, S. M., & Khani, Z. (2012). Identification and classification of plastic resins using near infrared reflectance spectroscopy. *International Journal of Mechanical and Mechatronics Engineering*, *6*(5), 213-220. Retrieved in 2023, April 4, from https://publications.waset.org/11237/pdf
9. Li, J., Wu, G., & Xu, Z. (2015). Tribo-charging properties of waste plastic granules in process of tribo-electrostatic separation. *Waste Management*, *35*, 36-41. http://dx.doi.org/10.1016/j.wasman.2014.10.001. PMid:25453321.
10. Fraunholcz, N. (2004). Separation of waste plastics by froth flotation – a review, part I. *Minerals Engineering*, *17*(2), 261-268. http://dx.doi.org/10.1016/j.mineng.2003.10.028.
11. Burat, F., Güney, A., & Kangal, M. O. (2009). Selective separation of virgin and post-consumer polymers (PET and PVC) by flotation method. *Waste Management*, *29*(6), 1807-1813. http://dx.doi.org/10.1016/j.wasman.2008.12.018. PMid:19155169.
12. Carvalho, T., Durão, F., & Ferreira, C. (2010). Separation of packaging plastics by froth flotation in a continuous pilot plant. *Waste Management*, *30*(11), 2209-2215. http://dx.doi.org/10.1016/j.wasman.2010.05.023. PMid:20576423.
13. Wang, C.-Q., Wang, H., Fu, J.-G., & Liu, Y.-N. (2015). Flotation separation of waste plastics for recycling - a review. *Waste Management*, *41*, 28-38. http://dx.doi.org/10.1016/j.wasman.2015.03.027. PMid:25869841.
14. Pita, F., & Castilho, A. (2017). Separation of plastics by froth flotation. The role of size, shape and density of the particles. *Waste Management*, *60*, 91-99. http://dx.doi.org/10.1016/j.wasman.2016.07.041. PMid:27478025.
15. Wang, H., Zhang, Y., & Wang, C. (2019). Surface modification and selective flotation of waste plastics for effective recycling - a review. *Separation and Purification Technology*, *226*, 75-94. http://dx.doi.org/10.1016/j.seppur.2019.05.052.
16. Kannan, P., Lakshmanan, G., Shoaibi, A. A., & Srinivasakannan, C. (2017). Polymer recovery through selective dissolution of co-mingled post-consumer waste plastics. *Progress in Rubber, Plastics and Recycling Technology*, *33*(2), 75-84. http://dx.doi.org/10.1177/147776061703300202.
17. Yuan, H., Fu, S., Tan, W., He, J., & Wu, K. (2015). Study on the hydrocyclonic separation of waste plastics with different density. *Waste Management*, *45*, 108-111. http://dx.doi.org/10.1016/j.wasman.2015.01.037. PMid:25736578.
18. Pita, F., & Castilho, A. (2016). Influence of shape and size of the particles on jigging separation of plastics mixture. *Waste Management*, *48*, 89-94. http://dx.doi.org/10.1016/j.wasman.2015.10.034. PMid:26560809.
19. Fu, S., Fang, Y., Yuan, H., Tan, W., & Dong, Y. (2017). Effect of the medium's density on the hydrocyclonic separation of waste plastics with different densities. *Waste Management*, *67*, 27-31. http://dx.doi.org/10.1016/j.wasman.2017.05.019. PMid:28527864.
20. Quelal, W. O. M., Velázquez-Martí, B., & Gisbert, A. F. (2022). Separation of virgin plastic polymers and post-consumer mixed plastic waste by sinking-flotation technique. *Environmental Science and Pollution Research International*, *29*(1), 1364-1374. http://dx.doi.org/10.1007/s11356-021-15611-w. PMid:34350580.
21. Dodbiba, G., Sadaki, J., Okaya, K., Shibayama, A., & Fujita, T. (2005). The use of air tabling and triboelectric separation for separating a mixture of three plastics. *Minerals Engineering*, *18*(15), 1350-1360. http://dx.doi.org/10.1016/j.mineng.2005.02.015.
22. Pongstabodee, S., Kunachitpimol, B., & Damronglerd, S. (2008). Combination of three-stage sink-float method and selective flotation technique for separation of mixed post-consumer plastic waste. *Waste Management*, *28*(3), 475-483. http://dx.doi.org/10.1016/j.wasman.2007.03.005. PMid:17493796.
23. Hori, K., Tsunekawa, M., Ueda, M., Hiroyoshi, N., Ito, M., & Okada, H. (2009). Development of a new gravity separator for plastics a hybrid-jig. *Materials Transactions*, *50*(12), 2844-2847. http://dx.doi.org/10.2320/matertrans.M-M2009825.

24. Zhao, S., Zhu, L., & Li, D. (2015). Characterization of small plastic debris on tourism beaches around the South China Sea. *Regional Studies in Marine Science*, *1*, 55-62. http://dx.doi.org/10.1016/j.rsma.2015.04.001.
25. Masura, J., Baker, J., Foster, G., & Arthur, C. (2015). *Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments*. Silver Spring: National Oceanic and Atmospheric Administration. Retrieved in 2023, April 4, from http://hdl.handle.net/11329/1076
26. Quinn, B., Murphy, F., & Ewins, C. (2017). Validation of density separation for the rapid recovery of microplastics from sediment. *Analytical Methods*, *9*(9), 1491-1498. http://dx.doi.org/10.1039/C6AY02542K.
27. Schulz, N. F. (1970). Separation efficiency. *Transactions of the Society for Mining, Metallurgy, and Exploration, Inc.*, *247*, 81-87.
28. Kangal, M. O. (2010). Selective flotation technique for separation of PET and HDPE used in drinking water bottles. *Mineral Processing and Extractive Metallurgy Review*, *31*(4), 214-223. http://dx.doi.org/10.1080/08827508.2010.483362.
29. Carvalho, M. T., Ferreira, C., Santos, L. R., & Paiva, M. C. (2012). Optimization of froth flotation procedure for poly (ethylene terephthalate) recycling industry. *Polymer Engineering and Science*, *52*(1), 157-164. http://dx.doi.org/10.1002/pen.22058.
30. Saisinchai, S. (2014). Separation of PVC from PET/PVC mixtures using flotation by calcium lignosulfonate depressant. *Engineering Journal*, *18*(1), 45-53. http://dx.doi.org/10.4186/ej.2014.18.1.45.
31. Wang, H., Wang, C.-Q., Fu, J.-G., & Gu, G.-H. (2014). Flotability and flotation separation of polymer materials modulated by wetting agents. *Waste Management*, *34*(2), 309-315. http://dx.doi.org/10.1016/j.wasman.2013.11.007. PMid:24355830.
32. Pita, F., & Castilho, A. (2019). Plastics floatability: effect of saponin and sodium lignosulfonate as wetting agents. *Polímeros: Ciência e Tecnologia*, *29*(3), e2019035. http://dx.doi.org/10.1590/0104-1428.01419.

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