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A sustainable approach to separate and recover indium and tin from spent indium–tin oxide targets†

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This study proposed an innovative method to separate and recover indium and tin from spent indium–tin-oxide (ITO) targets. ITO was first dissolved using concentrated HCl and then the leaching solution was distilled to recycle HCl and crystallize indium and tin ions. Next, the obtained crystals were transferred into $SOCl_2$ solution under refluxing to remove the crystal water. By simply fractionating the mixture, anhydrous indium chloride, tin tetrachloride, and $SOCl_2$ can be separated in a single operation. The recovery rate of $InCl_3$ was *ca.* 99.6% with a purity of *ca.* 99.8%, while *ca.* 98.0% of $SnCl_4$ was recovered with a purity of *ca.* 99.7%. Both the recovery rates and purities are the highest reported so far. Since all the reagents used in this process were carefully designed, almost all of the reagents can be reused. This is an environmentally friendly, economical and practical method to efficiently recycle ITO targets.

1. Introduction

Indium–tin oxide (ITO) is a conductive solid with the characteristics of transparency and colorlessness. The excellent electrical conductivity, optical transparency and thermal reflection of ITO make it an ideal material for flat-panel displays,[1–6] solar cells,[7–9] organic light-emitting diodes,[10,11] anti-static coatings,[12] electromagnetic shielding,[13] and so on. Approximately 65% of indium production worldwide was consumed in the configuration of ITO, while the majority of ITO was used in coating materials for displays. ITO targets are composed of In_2O_3 and SnO_2 with a mass ratio of 10 wt%, 5 wt%, or 3 wt% SnO_2.[14] ITO films are synthesized by sputtering ITO targets. According to the United States Geological Survey, in the sputtering process, only 15% of ITO was utilized to make LCDs.[15] Target utilization (TU) for a planar target was *ca.* 30%,[16,17] while the TU for a rotary target was around 70–80%.[17,18] It's obvious that the spent ITO targets should be recovered. Of course, the spent targets can be easily recycled for producing new ITO layers by grinding them into fine powder and mixing them with fresh ITO powder. Nevertheless, it is still of great significance to separate indium from spent ITO targets, due to the continuously growing demands for indium, gallium, and zinc oxide (IGZO),[19,20] copper, indium, gallium, and selenium (CIGS), *etc.*[21] IGZO, a better semiconducting material, which was considered to be the most promising thin-film transistor for the next generation flat panel displays, has shown great potential for replacing ITO.[22,23] At present, there are mainly five methods to separate and recycle indium from spent ITO targets: vacuum-chlorinated separation,[24,25] vacuum carbonization reduction,[26] solvent extraction separation,[27–29] ion-exchange,[30,31] and biological metallurgy separation.[32]

In our previous study, HCl gas was utilized to react with In_2O_3 and SnO_2 at 373 K for 60 min to obtain $InCl_3$ and $SnCl_4$.[25] The reaction products ($SnCl_4$ and $InCl_3$) were recycled respectively in a nitrogen atmosphere at 573 K and 673 K by evaporation. He *et al.*[26] recycled ITO *via* a carbon (50 wt%) reduction at 1223 K under 1 Pa for 30 min, and pure indium could be selectively recovered around the condensing temperature. Yang *et al.*[27] studied the recovery of indium using extractants cyanex 923, cyanex 272, TBP and D2EHPA, respectively in hydrochloric and sulfuric acid solution, and *ca.* 99 wt% of indium was recovered with a purity around 90%. Swain *et al.*[28] reported a recovery rate of 97.78% for Sn with 99% purity by using the extractant cyanex 272.28 LópezDíaz-Pavón *et al.*[31] utilized the cationic ion-exchange resin Lewatit K-2621 to separate indium from tin. Higashi *et al.*[32] recovered indium by adding the *Shewanella* algae into the leached solution to concentrate the indium for 680 times. Unfortunately, all these methods mentioned above suffer from their own drawbacks, namely, vacuum-chlorinated separation has relatively low recovery rate and operates at high temperature, vacuum carbonization reduction process operates at even higher temperature and low pressure; solvent extraction

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† Electronic supplementary information (ESI) available: Photographs for the spent ITO target materials, the recovered mixed crystal hydrates of $InCl_3$ and $SnCl_4$, the setup of dehydrating process, and the as-filtrated anhydrous $InCl_3$ and $SnCl_4$, and XRD patterns of the hydrate obtained from $SnCl_4$–HCl solution and the standard $SnCl_4\cdot5H_2O$ crystal. See DOI: 10.1039/c7ra11976c

consumes lots of water and organic reagents; ion-exchange and biological metallurgy are hard to operate in large scale.[33] Based on this, an innovative sustainable approach to separate and recover indium and tin efficiently is highly desired. In this study, a scalable, economical and sustainable approach, dissolution–distillation–dehydration–fractionation (DDDF), has been developed. The recovery rates and purities of $InCl_3$ and $SnCl_4$ are the highest reported so far, indicating this approach is very promising for practical application.

2. Experimental section

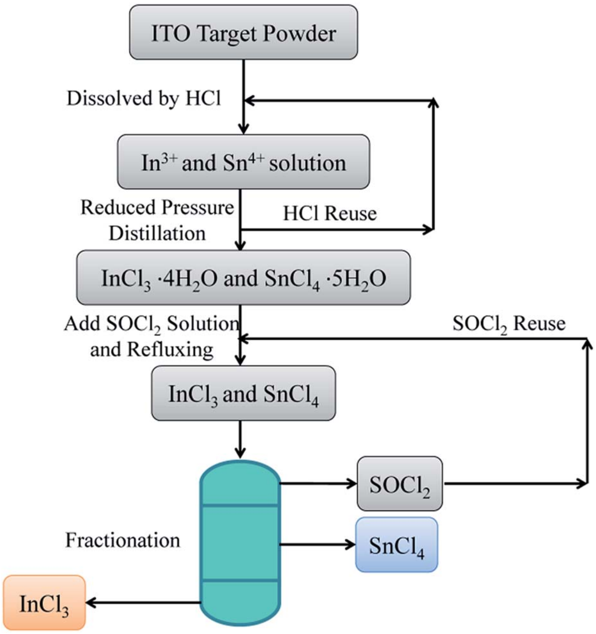
2.1 Materials and methods

The spent ITO target material (Wako chemicals), was first ground to fine powder, as shown in Fig. S1 (ESI†) for composition analysis. The physical properties of the spent ITO powder (density, size distribution) are described in the ESI.† The composition of the spent ITO targets were examined by XRF (Rigaku supermini WDXRF) and the mass fraction of each component in the ITO target was measured by standard FP quantification program (SQX) analysis, and the data are shown in Table 1. Since SQX is only a semi-quantitative analysis method, the actual mass fraction of indium and tin in the spent target was determined by ICP-OES (PerkinElmer® Optima 5300 DV) after dissolving the ITO target powder using aqua regia. Table S1 (ESI†) summarizes the mass of In^{3+}, Sn^{4+}, and Zn^{2+} determined by ICP-OES for three ITO powder samples with different masses. The average mass fraction for these species is also shown in Table 1, from which it is clear that the mass ratio of In_2O_3 to SnO_2 is around 95 : 5 with ZnO as the main impurity.

The DDDF separation and recovery process is shown in Scheme 1. The process can be divided into four steps: dissolution, distillation or crystallization, dehydration, and fractionation. First, the spent ITO powder was dissolved completely with HCl, and then the leached solution was distilled to obtain the crystal of metal chloride hydrates. Next, the crystal was dehydrated by a dehydrating agent (*i.e.*, $SOCl_2$) under refluxing. Last, the resultant solution was fractionated to separate anhydrous $InCl_3$, $SnCl_4$, and $SOCl_2$. For a typical separation and recovery process, ITO target powder was first dissolved by concentrated HCl, and indium and tin oxides in the ITO were dissolved into the leaching solution. The distillation process was conducted in a rotary evaporator equipped with an oil bath and a vacuum pump. After distillation, the mixture of indium chloride and tin chloride hydrates were left in the bottom of the flask. The mixed hydrates were then transferred into a flask, followed by the addition of an appropriate amount of $SOCl_2$ for dehydrating. Because the dehydration process required refluxing $SOCl_2$, the flask was equipped with a condenser-Allihn type and a mandarin heater. During this step, the crystal water in indium chloride and tin chloride hydrates reacted with $SOCl_2$, leaving the anhydrous $InCl_3$ and $SnCl_4$ in the solution. It is well known that anhydrous $SnCl_4$ is a liquid at room temperature. Anhydrous $InCl_3$ has no/little solubility in both $SnCl_4$ and $SOCl_2$, while $SnCl_4$ has a considerable solubility in $SOCl_2$ solution as shown in eqn (1):[34]

Table 1 The chemical composition of the spent ITO target determined by SQX analysis of XRF and ICP-OES

Composition by XRF	In_2O_3	SnO_2	ZnO	Others
Mass (wt%)	94.92	4.94	0.12	0.02
Composition by ICP	In^{3+}	Sn^{4+}	Zn^{2+}	
Mass (wt%)	95.17	4.71	0.12	



Scheme 1 Illustration of the green approach to separate indium and tin from the spent ITO target.

$$2SOCl_2 + SnCl_4 \rightleftharpoons 2SOCl^+ + SnCl_6^{2-} \quad (1)$$

In the fourth step, anhydrous $InCl_3$, $SnCl_4$, and $SOCl_2$ can be separated from each other by simply fractionating the mixture. $SOCl_2$, which has the lowest boiling point around 76 °C, was removed from the mixture first. After that, $SnCl_4$ was also removed at approximately 114 °C. At last, anhydrous $InCl_3$ powder (melting point: 586 °C, boiling point: 800 °C) was left at the bottom of the flask. The hydrates of indium chloride and tin chloride from the distillation process and the anhydrous $InCl_3$ from the fractionation process were then analyzed with XRD (Rigaku® Smart lab). Since indium chloride hydrate, tin chloride hydrate, and anhydrous indium chloride are sensitive to the moisture in the air, an air-sensitive sample holder (Rigaku® Mini Flex accessories) was utilized to isolate the samples from the air during the XRD measurements.

2.2 HCl leaching

The spent ITO target was crushed and milled to fine powder with an average particle size of around 6.781 μm, as shown in Fig. S2 (ESI†). The powder was then dissolved in HCl solution under different acid concentrations, solid–liquid (S/L) ratios, temperatures, and leaching times. The concentration of HCl was varied from 1 mol L^{-1} to 9 mol L^{-1} (*i.e.*, 1, 3, 5, 7, and 9 mol L^{-1}) with an S/L ratio ranging from 1 g L^{-1} to 20 g L^{-1} (*i.e.*, 1, 5, 10, and 20 g L^{-1}). The leaching temperature was varied from 20 °C to 90 °C (*i.e.*, 20, 40, 60, 80, and 90 °C) with the leaching time ranging from 30 min to 120 min (*i.e.*, 30, 50, 70, 90, and 120 min). The leaching process was conducted in a beaker equipped with a stirring hotplate (RET control-visc, IKA) to control the stirring speed and leaching temperature. HCl (37%, reagent grade, Sigma-Aldrich) was used as received.

2.3 Distillation, dehydration, and fractionation

The leached solution was then transferred to a rotary evaporator (Eyela®N-1100D) equipped with an oil bath operated at 90 °C and a vacuum pump (Eyela®NVC-2200) with a vacuum degree of 0.09 MPa for 2 h. After that, the hydrates remained at the bottom of the flask were transferred to a new flask equipped with a mandarin heater and a condenser for dehydration. $SOCl_2$ (99.5%, analytical pure, Sigma-Aldrich) was used as received. The ratio of $SOCl_2$ to hydrate was 1.2 mL g^{-1}. $SOCl_2$ was refluxed at 75 °C for 2 h to dehydrate the mixture. During this process, SO_2 and HCl gas kept bubbling out of the solution till the dehydration process reached the ending point. After the bubbling stopped, the fractionation process started. The flask was equipped with a Vigreux fractionating column to separate $SOCl_2$ and anhydrous $SnCl_4$ at 114 °C for 2 h (Fig. S7, ESI†) through which $SOCl_2$ was distilled out of the flask, leaving anhydrous $SnCl_4$ and $InCl_3$ at the bottom of the flask. At last, anhydrous $SnCl_4$ was also distilled out of the flask and thus separated from $InCl_3$.

3. Results and discussion

3.1 Dissolution of the spent ITO targets

The optimum leaching condition was investigated by dissolving the spent ITO target in various HCl-based solvents with different acid concentrations, S/L ratios, temperatures, and times. The stirring rate was fixed at 500 rpm (peripheral velocity: 31.4 cm s^{-1}). As can be seen from Fig. 1, the mixed solvent composed of 5 M HCl with an S/L ratio of 10 g L^{-1} and leaching temperature of 40 °C all indium and tin could be dissolved after 120 min. The leaching results of the optimum condition are given in Table 2, which shows that more than 99.9% of indium and tin can be dissolved (Table S1, ESI†). The main impurities are zinc and aluminum.

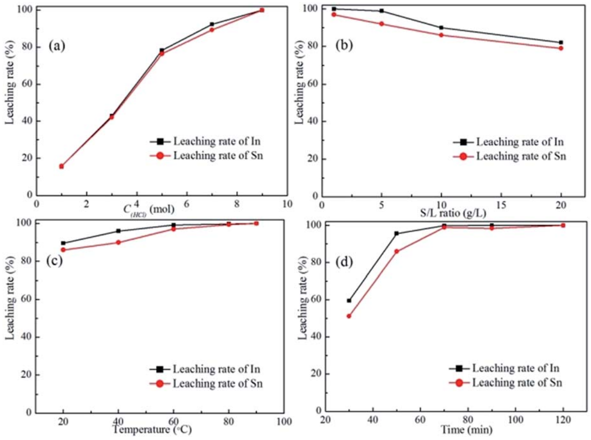


Fig. 1 Leaching of the spent ITO target under different conditions: (a) the effect of HCl concentration on the leaching rate of ITO target with the temperature of 20 °C, the leaching time of 60 min, and the S/L ratio of 20 g L^{-1}, (b) the effect of S/L ratio on the leaching rate of ITO target with the temperature of 20 °C, the leaching time of 60 min, and HCl concentration of 5 mol L^{-1}, (c) the effect of leaching temperature on the leaching rate of ITO target with the leaching time of 60 min, the S/L ratio of 10 g L^{-1}, and HCl concentration of 5 mol L^{-1}, and (d) the effect of leaching time on the leaching rate of ITO target with the temperature of 40 °C, the S/L ratio of 10 g L^{-1}, and HCl concentration of 5 mol L^{-1}.

Table 2 The chemical composition of the spent ITO target powder obtained from leaching

ITO powder (g)	In^{3+} (ppm)	Sn^{4+} (ppm)	Zn^{2+} (ppm)	Al^{3+} (ppm)	Others
3.275	8570	425	10.5	2.44	<1 ppm
3.158	8263	429	10.1	2.35	<1 ppm
3.098	8106	402	9.93	2.31	<1 ppm

3.2 Distillation and dehydration process

After the dissolution step, the leaching solution was distilled to recycle HCl. In addition, a mixed hydrate crystal was obtained in this step, which was analyzed with XRD and ICP-OES. For some reason we do not have the standard card info of $InCl_3\cdot 4H_2O$, and thus, the obtained XRD pattern was compared with $InCl_3\cdot 4H_2O$ and $SnCl_4\cdot 5H_2O$. The details about the preparation of the hydrate metal chloride can be seen from the ESI† and the XRD patterns for the standard $SnCl_4\cdot 5H_2O$ crystal and as-distilled $SnCl_4$ hydrate are shown in Fig. S3 (ESI†). As can be seen from Fig. 2, all of the characteristic peaks in $InCl_3\cdot 4H_2O$ and $SnCl_4\cdot 5H_2O$ patterns appeared in the as-distilled mixed hydrate crystal pattern except that few peaks with very low intensity were observed for the as-distilled mixed hydrate crystal but these peaks did not appear in both $InCl_3\cdot 4H_2O$ and $SnCl_4\cdot 5H_2O$, implying that these weak peaks are probably attributed to the characteristic peaks of the impurities in the spent ITO target material. Therefore, the main composition of the mixed crystal should be $InCl_3\cdot 4H_2O$ and $SnCl_4\cdot 5H_2O$. Based on this, the ratio of indium and tin hydrate can be calculated by dissolving a certain amount of the as-distilled mixed crystal (as shown in Fig. S3, ESI†) and analyzing with ICP-OES. The mixed crystal obtained in this step was determined to contain 94.38 wt% $InCl_3\cdot 4H_2O$ and 5.53 wt% $SnCl_4\cdot 5H_2O$ (Table S2, ESI†). In order to separate indium from tin, $SOCl_2$ was added to dehydrate the crystal, and as a result, anhydrous $InCl_3$ and $SnCl_4$ can be obtained according to eqn (2) and (3).[35] According to the composition of the hydrate obtained from XRD and ICP-OES, 1 g hydrate contains 0.9438 g $InCl_3\cdot 4H_2O$ and 0.0553 g $SnCl_4\cdot 5H_2O$, which means 1 g hydrate would consume 0.991 ml of $SOCl_2$ solution. To ensure a thorough dehydration, the S/L ratio of the crystal

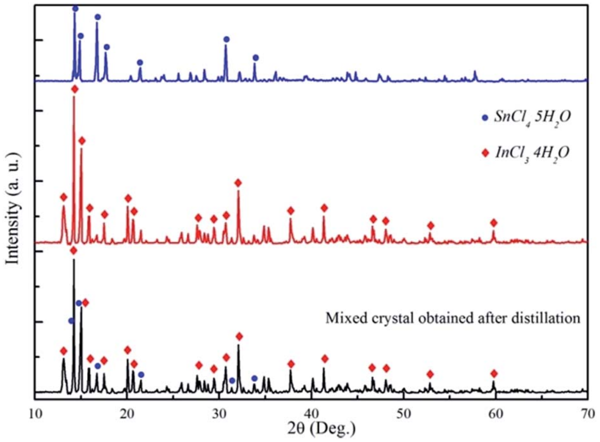


Fig. 2 XRD patterns of the mixed hydrate crystal obtained after distillation, $InCl_3 \cdot 4H_2O$, and $SnCl_4 \cdot 5H_2O$.

hydrate and $SOCl_2$ was set as 1 g/1.2 ml. HCl and SO_2 gases were emitted during the dehydration process, which are hazardous to the environment. Proper methods were adopted to separate or dispose these hazardous gases. By utilizing the different solubility of HCl and SO_2 in water, the majority of HCl can be separated from SO_2 in hot water.[36] After which, HCl can be used in the leaching process, while SO_2 can be liquefied for storage and sale (Table S3, ESI†). HCl and SO_2 gases can also be disposed with $Ca(OH)_2$ *etc.* in the dry scrubbing process[37,38] (Table S3, ESI†). The setup for dehydrating is shown in Fig. S5 (ESI†).

$$InCl_3 \cdot 4H_2O + 4SOCl_2 \rightarrow InCl_3 + 4SO_2\uparrow + 8HCl\uparrow \quad (2)$$

$$SnCl_4 \cdot 5H_2O + 5SOCl_2 \rightarrow SnCl_4 + 5SO_2\uparrow + 10HCl\uparrow \quad (3)$$

3.3 Fractionation process

After dehydrating, the mixture of anhydrous $SnCl_4$ and $SOCl_2$ was heated for fractionation. Since anhydrous $InCl_3$ is insoluble in $SnCl_4$ and $SOCl_2$ (Fig. S6, ESI†), the fractionation process would not be affected by the appearance of anhydrous $InCl_3$. Fig. 3 shows the binary liquid–liquid phase diagram of anhydrous $SnCl_4$ and $SOCl_2$. The molar ratio of anhydrous $SnCl_4$ in the solution was 2.2% at this point. With the distilling of $SOCl_2$, the molar ratio of anhydrous $SnCl_4$ kept increasing. At last, almost all $SOCl_2$ was vaporized into the gas phase, which required 5 theoretical plates to reach 99.9% pure of $SOCl_2$, as shown in Fig. 3. Also, according to the shape of the binary phase diagram, anhydrous $SnCl_4$ would not form azeotrope with $SOCl_2$. Afterwards, $SnCl_4$ can also be distilled out of the flask at around 114 °C, leaving the white powder at the bottom of the flask. As shown in Fig. 4, the XRD pattern reveals that the white powder (shown in Fig. S8, ESI†) was anhydrous $InCl_3$ and the purity was 99.8 wt% (Table S5, ESI†). To examine the recovery rate of $InCl_3$ and $SnCl_4$, three parallel experiments were done and analyzed with ICP-OES, and the data are shown in Table 3. The recovery rate of indium in the whole process was calculated to be approximately 99.6%. Anhydrous $SnCl_4$ was separated from $SOCl_2$ solution by distillation due to the lower boiling point of $SOCl_2$. $SnCl_4$ was analyzed with ICP-OES, and the data are also shown in Table 3. The recovery rate of tin was calculated to be around 98.5%, while the purity of $SnCl_4$ was determined to be *ca.* 99.7% (Table S5, ESI†).

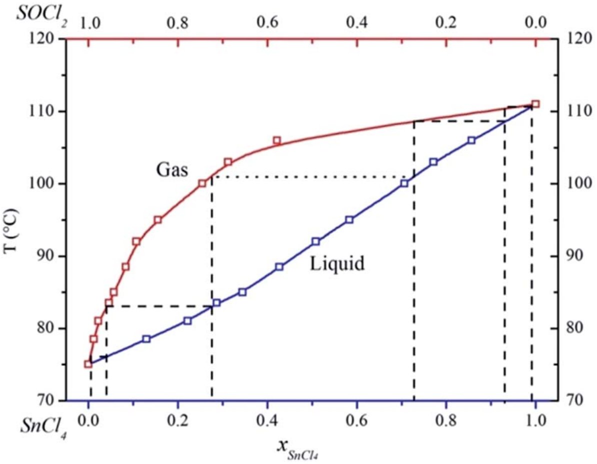


Fig. 3 Binary liquid–liquid phase diagram of anhydrous $SnCl_4$ and $SOCl_2$.

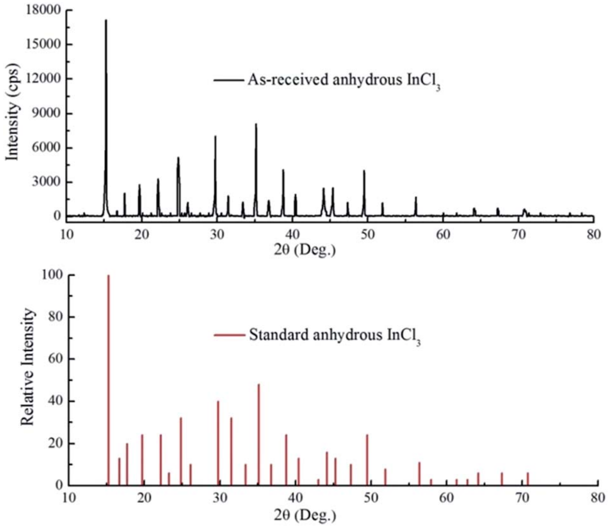


Fig. 4 XRD patterns of the as-recovered $InCl_3$ and the standard anhydrous $InCl_3$.

3.4 Comparison of DDDF with ion-exchange and solvent extraction methods

Since vacuum chlorinated separation and vacuum carbonization reduction process operates at a high temperature (1000–1300 K) and high vacuum degree (*e.g.*, 1 Pa), which requires more sophisticated equipment, and are mainly designed for the recycling of indium and tin from waste LCDs. A comparison has been made between this method with solvent extraction and ion-exchange methods to demonstrate the superiority of the

Table 3 Recovery rate of indium and tin from spent ITO target material measured by ICP-OES

	Dissolution (g)	Distillation (g)	Dehydration (g)	Fractionation (g)	Recovery rate (%)				
ITO	In^{3+}	Sn^{4+}	Hydrate	$InCl_3$	$SnCl_4$	$InCl_3$	$SnCl_4$	$InCl_3$	$SnCl_4$
5.079	3.987	0.1976	10.77	7.656	0.4311	7.655	0.4305	99.67	99.28
5.018	3.939	0.1953	10.64	7.557	0.4199	7.556	0.4192	99.58	97.81
5.027	3.946	0.1956	10.66	7.570	0.4232	7.569	0.4228	99.57	98.50

Table 4 Comparison of recycling 1 kg of ITO targets with solvent extraction, ion-exchange, and DDDF process[a]

		Energy consumption	Products		
Methods	Reagents consumption	(kW)	Indium	Tin	Secondary wastes
Solvent extraction with D2EHPA[29]	H_2O: 1164.42 L H_2SO_4: 54.33 L HCl: 31.25 L D2EHPA: 50 L Kerosene: 200 L	125.8	R: 97.4% P: 99.8%	Sn^{4+} in D2EHPA	1000 L 1 M H_2SO_4 250 L 20% D2EHPA 250 L 1.5 M HCl
Solvent extraction with TBP[29]	H_2O: 916.67 L HCl: 83.33 L TBP: 273 L Kerosene: 727 L	85.8	R: 99.3% P: 96.5%	Sn^{4+} in TBP	1000 L 1 M HCl 1000 L 1 M TBP
Ion-exchange with DODGAA-IL[30]	H_2O: 1761.45 L HCl: 2.5 L HNO_3: 67.65L NaOH: 0.8468 kg XAF-7 resin: 30.2 kg DODGAA: 7.55 kg $[C_4mim][Tf_2N]$: 7.55 kg Acetone: 151 L	702.4	R: 92.2% P: 96.9%	R: 87.3% P: 48.9%	151 L acetone 1570 L pH = 2 HNO_3 130.8 L 2.5 M HNO_3 130.8 L 5 M HNO_3 45 kg DODGAA-IL resin
DDDF and handling of HCl and SO_2 mixed gas	H_2O: 7.5 L HCl: 2.5 L $SOCl_2$: 10 L Reuse: 10 L Na_2SO_3 16.39 L H_2O	50.8 —	R: 99.6 P: 99.8	R: 98.6 P: 99.7	10 L Na_2SO_3 solution 8.72 kg $CaSO_3$, 8.72 kg $CaCl_2$, and 6.36 kg H_2O
	Or dispose: 17.45 kg $Ca(OH)_2$	—	Byproducts: HCl solution and SO_2		

[a] R: recovery rate, P: purity.

DDDF process in separate and recycle indium and tin from spent ITO targets. The evaluation was performed based on the previous reports for recycling 1 kg spent ITO target with solvent-extraction, ion-exchange and DDDF process in a laboratory scale. As shown in Table 4 which summarizes the information about the secondary wastes (Table S3, ESI†), energy consumptions (Table S6, ESI†), products (Table S7, ESI†), and reagents consumptions (Table S8, ESI†) in these processes. It's evident that the DDDF process consumes less energy, reagents, and produces the least secondary wastes with the highest recovery rate and purity of the products. While in the solvent extraction process only indium was separated and recovered, and tremendous amount of chemicals (extractants, diluents, stripping reagents) and water were consumed which generated huge amount of secondary wastes. The extractants were not counted as the secondary wastes, since they can be used multiple times. Both indium and tin can be separated and recovered with a lower recovery rate and purity in the ion-exchanged process, while an enormous amount of chemicals (extractants, ionic liquid, solvent, and resin) and water were consumed and finally became secondary wastes. In contrast, the DDDF process only requires general equipment, which makes it easy to scale up. Based on these, it's safe to say the DDDF process is a scalable, economical and sustainable approach.

4. Conclusions

In summary, the DDDF process developed in this study is highly efficient in separating and recovering indium and tin from spent ITO targets. By tailoring the reagents used in this process, almost all the reagents could be recycled and reused, and only sulfur dioxide and hydrogen chloride were emitted, which can also be easily collected and disposed. Compared with other processes reported previously, this method has the advantages such as: consuming less energy, minimizing the reagents consumption, scalable mass production, higher recovery rate, and environmental benignity. 99.6% of indium in the form of anhydrous $InCl_3$ with a purity of 99.8% was separated and recovered, while 98.6% of tin in the form of $SnCl_4$ was separated and recovered, which has a purity of 99.7%. The purities and recovery rates of indium and tin are the highest among all the values reported for various processes. Furthermore, a complete separation of indium and tin was achieved in a simple fractionation step. Therefore, this method has taken full advantage of the property of anhydrous $SnCl_4$, $InCl_3$, and $SOCl_2$ to separate indium and tin from the spent ITO targets. $SOCl_2$ plays two roles in this process: the first role is to react with $InCl_3 \cdot 4H_2O$ and $SnCl_4 \cdot 5H_2O$ to form anhydrous $InCl_3$ and $SnCl_4$, and the second role is to separate $InCl_3$ and $SnCl_4$ from $SOCl_2$ due to the lowest boiling point of the latter. These important roles of $SOCl_2$ enable the whole separation and recovery process to function efficiently. Another important reagent used in this process is HCl, which also has two important roles: (1) the relatively low boiling point of HCl enables it to be reused easily by simply heating at low temperature, and (2) the crystal resulted from the heating is metal chloride hydrates, which provide a great opportunity for $SOCl_2$ to react with them. More importantly, the final product is high purity of anhydrous $InCl_3$ and $SnCl_4$ rather than $InCl_3$ and $SnCl_4$ in aqueous solution, and thus there is no need for further procedures such as liquid–liquid extraction and ion-exchange process.

In brief, a scalable and highly efficient sustainable process has been developed to separate and recover indium and tin from spent ITO targets, which sheds light on recycling ITO targets economically.

Conflicts of interest

The authors declare no competing financial interest.

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