

Sustainable Recycling of Benzoic Acid Production Waste: Green and Highly Efficient Methods To Separate and Recover High Value-Added Conjugated Aromatic Compounds from Industrial Residues

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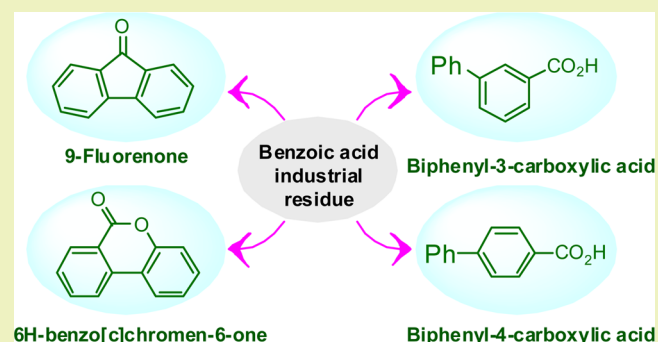
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S Supporting Information

ABSTRACT: Industrial residues formed in the industrial production of benzoic acid by cobalt-catalyzed oxidation of toluene are traditionally disposed as waste materials and often burnt or buried. It therefore may become a significant source of environmental pollution. In this report, we describe simple techniques to obtain high value conjugated aromatic compounds, including 9-fluorenone, 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid, from benzoic acid industrial residue using inexpensive alkalis and acids. The separation methods involve simple and mild procedures with high economic effectiveness and low environmental contamination.

KEYWORDS: Sustainable chemistry, Benzoic acid industrial residue, 9-Fluorenone, 6H-Benzo[c]chromen-6-one, Biphenyl carboxylic acids



INTRODUCTION

During the last century, the chemical industry has been largely dependent on nonrenewable fossil fuels as raw materials to produce commodity chemicals to meet human needs. However, the traditional nonideal technologies often lead to the accumulation of large amounts of waste in the production process. Therefore, sustainable development is gaining increased attention in the treatment and recovery of industrial chemical waste. Strategies that have been employed include reduction, recycling/reusing, and neutralization of industrial waste. Today many efforts have been devoted to waste recycling in order to achieve the dual purpose of recovering useful and high value-added compounds and reducing environmental pollution.^{1,2}

Benzoic acid is a common and important industrial chemical with a large number of applications in the manufacture of food preservatives,³ medicines,⁴ dyes,⁵ plasticizers,⁶ etc.^{7,8} Currently, the commercial production of benzoic acid is primarily based on the liquid-phase aerobic oxidation of toluene, which itself is an abundant side product from the coal and petroleum industry, in the presence of a homogeneous or emulsified cobalt catalyst.^{9,10} A considerable amount of benzoic acid industrial residue is formed in the process of benzoic acid production. The waste residue is an inflammable black solid with a strong odor and consists of benzoic acid, benzyl

benzoate, and 9-fluorenone as well as hundreds of other aromatic compounds.¹¹ Because of the lack of a cost-effective technology to recycle this residue, it is treated as a waste material and often burnt or buried. It therefore becomes a significant source of environmental pollution.

In recent years, increasing environmental and sustainable awareness and economic concern have led to research efforts aimed at separating and recovering high value-added products from benzoic acid industrial residue.^{12–14} However, current recycling approaches focus mainly on distillation techniques, and only a few chemicals with a low boiling point, such as benzoic acid, benzyl benzoate, and benzyl alcohol, could be recycled. As a result, many valuable chemicals are still disposed as waste.

Here, we report a new chemical recycling technique that allows for the recycling of four unique and high value-added conjugated aromatic compounds, namely, 9-fluorenone, 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid, from benzoic acid industrial residue. The benzoic acid industrial waste used in this study came from the Shijiazhuang Chemical Fiber Co., Ltd. in China. The

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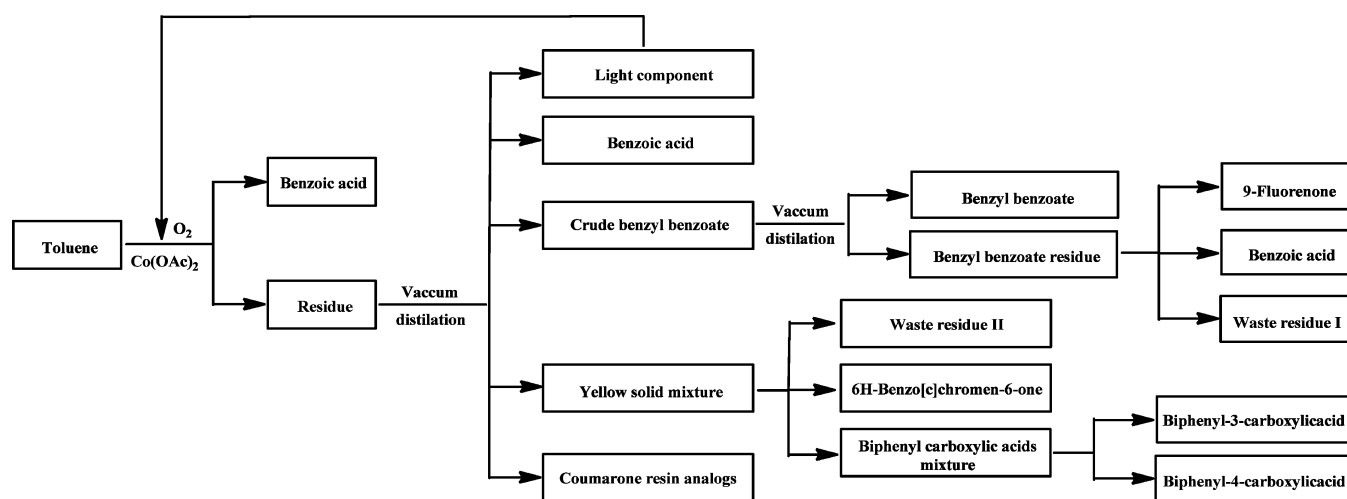


Figure 1. Block diagram of the overall treatment process of benzoic acid industrial residue.

technology we developed simply involves treatment of the residue with cheap alkalis and an inorganic acid followed by recrystallization with common organic solvents. The new separating and recovering methods can be conveniently performed with simple procedures under mild conditions. Each product can be obtained in relatively high yield and purity, and the organic solvents used in the recrystallization can be recycled and reused. This new protocol is therefore cost effective, more environmentally friendly, and should have potential for industrial applications.

It should be pointed out that except for 9-fluorenone, the other three compounds are identified and recovered for the first time, and to the best of our knowledge, there are no previous reports on the recycling of these compounds from the benzoic acid industrial residue. The compounds are all important building blocks and intermediates in organic synthesis and material chemistry, ranging from the synthesis of medicinal and pharmaceutical agents,¹⁵ liquid crystal materials,¹⁶ organic dyes,¹⁷ plastic additives,¹⁸ solar cells,¹⁹ organic optical limiter,²⁰ and even the preparation of organic light-emitting materials (OLEDs).^{21,22} Currently, the main source of biphenyl-4-carboxylic acid and biphenyl-3-carboxylic acid is from organic synthetic methods,^{23,24} and none of them have been scaled up to industrial production due to their high costs, poor atom economy, and potential environmental impact. Therefore, obtaining these two biphenyl carboxylic acids from the benzoic acid industrial residue would potentially provide an important and sustainable alternative to the chemical synthesis that typically involves a high energy input and utilizes expensive chemical reagents and solvents.

RESULTS AND DISCUSSION

Benzoic acid was synthesized by liquid-phase aerobic oxidation of toluene in the presence of cobalt(II) acetate. The industrial residue contains approximately 20% benzoic acid, 10% benzyl benzoate, and 4% 9-fluorenone, along with low percentages of many other conjugated aromatic compounds. The residue was originally treated in the company by distillation to recover benzoic acid, benzyl benzoate, and other products. As shown in Figure 1, the overall treatment process resulted in five primary components. The light component contains some low boiling oxidation intermediates, such as benzaldehyde and benzyl alcohol, which were collected from the top of the tower and

returned to the oxidation reactor for further conversion to benzoic acid. The second component is the original product benzoic acid. The third component is a crude mixture containing about 60% benzyl benzoate and 20% 9-fluorenone. This component was further treated in another distillation tower to obtain pure benzyl benzoate and new residue, which was named a benzyl benzoate residue. The fourth component is a yellow solid that contains a large number of high boiling aromatic compounds coined altogether as the yellow solid mixture. The last component is the bottom matrix and is composed of various polymeric tars along with some small molecular compounds with very high boiling points that are used as rubber additives. The results reported here are from our study on the separation and isolation of pure 9-fluorenone from the benzyl benzoate residue in the third component and the isolation and recovery of 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid from the fourth component, the yellow solid mixture.

Isolation of 9-Fluorenone from the Benzyl Benzoate Residue. Careful analysis of the benzyl benzoate residue by liquid chromatography–mass spectrometry (LC-MS) revealed that the residue contains about 40% 9-fluorenone, 10% benzyl benzoate, and dozens of other aromatic compounds. The boiling points of 9-fluorenone and benzyl benzoate are 342 and 324 °C, respectively. Therefore, it is difficult to separate benzyl benzoate and 9-fluorenone directly from the residue by distillation. The best result achieved by distillation was a crude 9-fluorenone with a purity of 85% after optimizing the height of the distillation column, number of plates, and distillation temperature as well as other conditions.¹⁴ However, further purification of 9-fluorenone by recrystallization proved to be very difficult due to the presence of impurities, mainly benzyl benzoate, which exhibits good mutual solubility with 9-fluorenone. We reasoned that a simple chemical procedure such as saponification would provide a straightforward solution to the purification. When the crude 9-fluorenone was treated with aq. NaOH, the benzyl benzoate impurity was completely hydrolyzed to the water-soluble sodium benzoate and benzyl alcohol, and the insoluble 9-fluorenone can be isolated in 89% purity after simple filtration. Further recrystallization with petroleum ether led to the isolation of pure 9-fluorenone in 29.2% yield, corresponding to 74.5% separation efficiency. We later found out that this protocol could be directly applied to

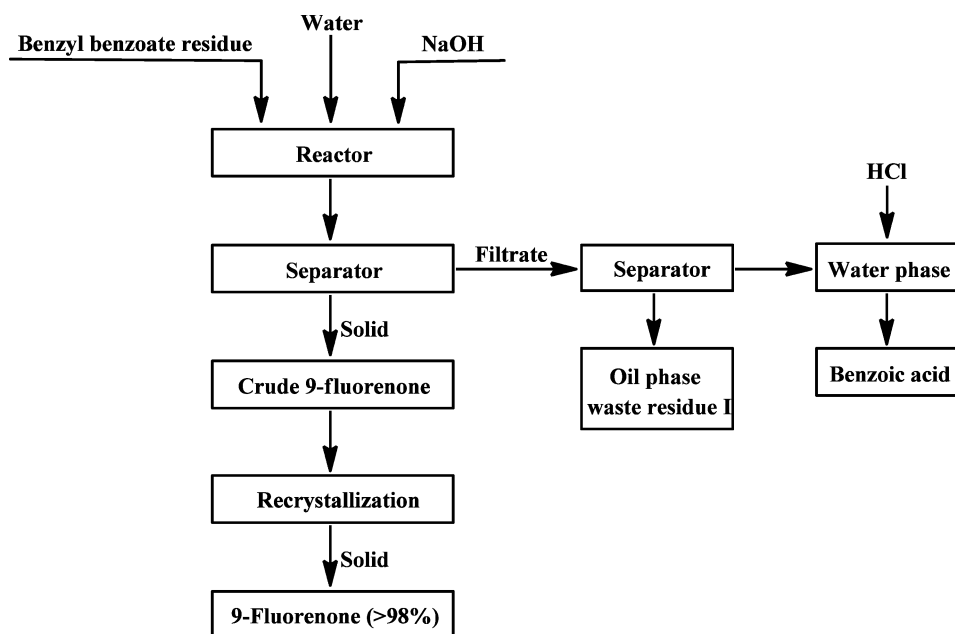


Figure 2. Process flow diagram of separation of 9-fluorenone and benzoic acid from the benzyl benzoate residue.

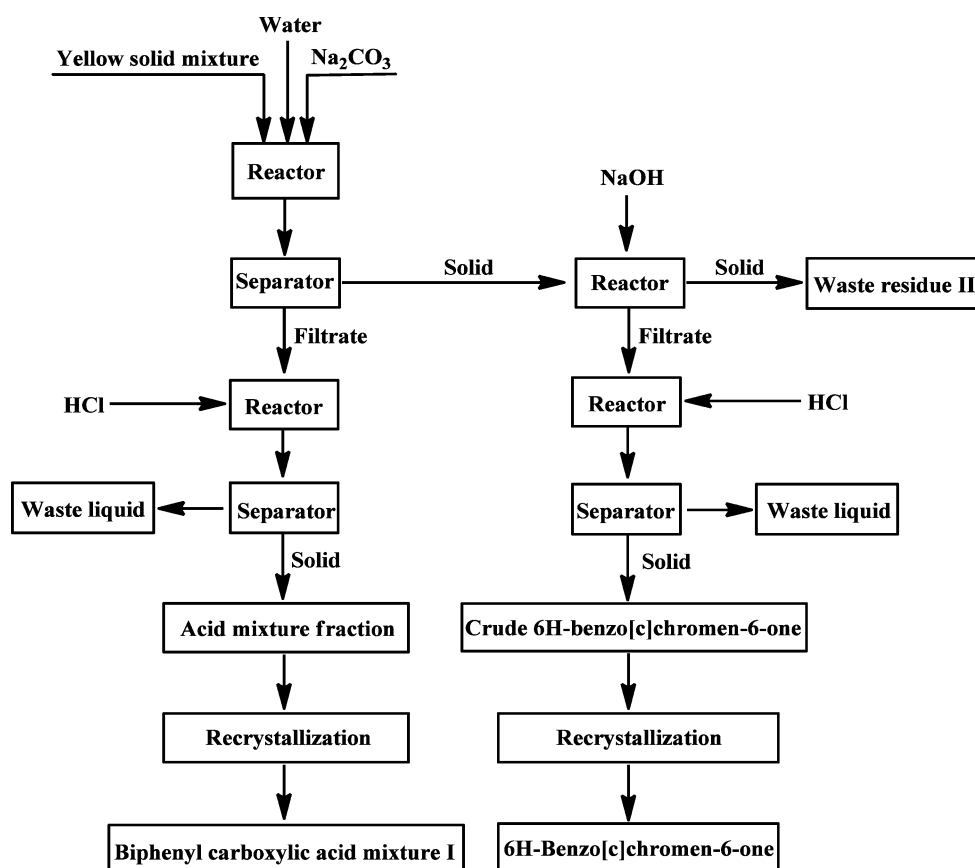


Figure 3. Process flow diagram of separation of 6H-benzo[c]chromen-6-one and biphenyl carboxylic acid mixture from the yellow solid mixture.

the crude benzyl benzoate residue without the need for a predistillation step. 9-Fluorenone obtained in this way was >90% pure, and further recrystallization from ethyl acetate and petroleum ether gave a pure product. The overall procedure led to the final separation of 9-fluorenone in an approximate 25–30% yield with a separation efficiency of 65–75%. In addition,

benzoic acid can be recovered from the aqueous solution after acidification. The process flow diagram is showed in Figure 2.

Isolation of 6H-Benzo[c]chromen-6-one, Biphenyl-3-carboxylic acid, and Biphenyl-4-carboxylic Acid from Yellow Solid Mixture. After successfully recovering 9-fluorenone from the benzyl benzoate residue, we moved our effort to the separation of the yellow solid mixture. This

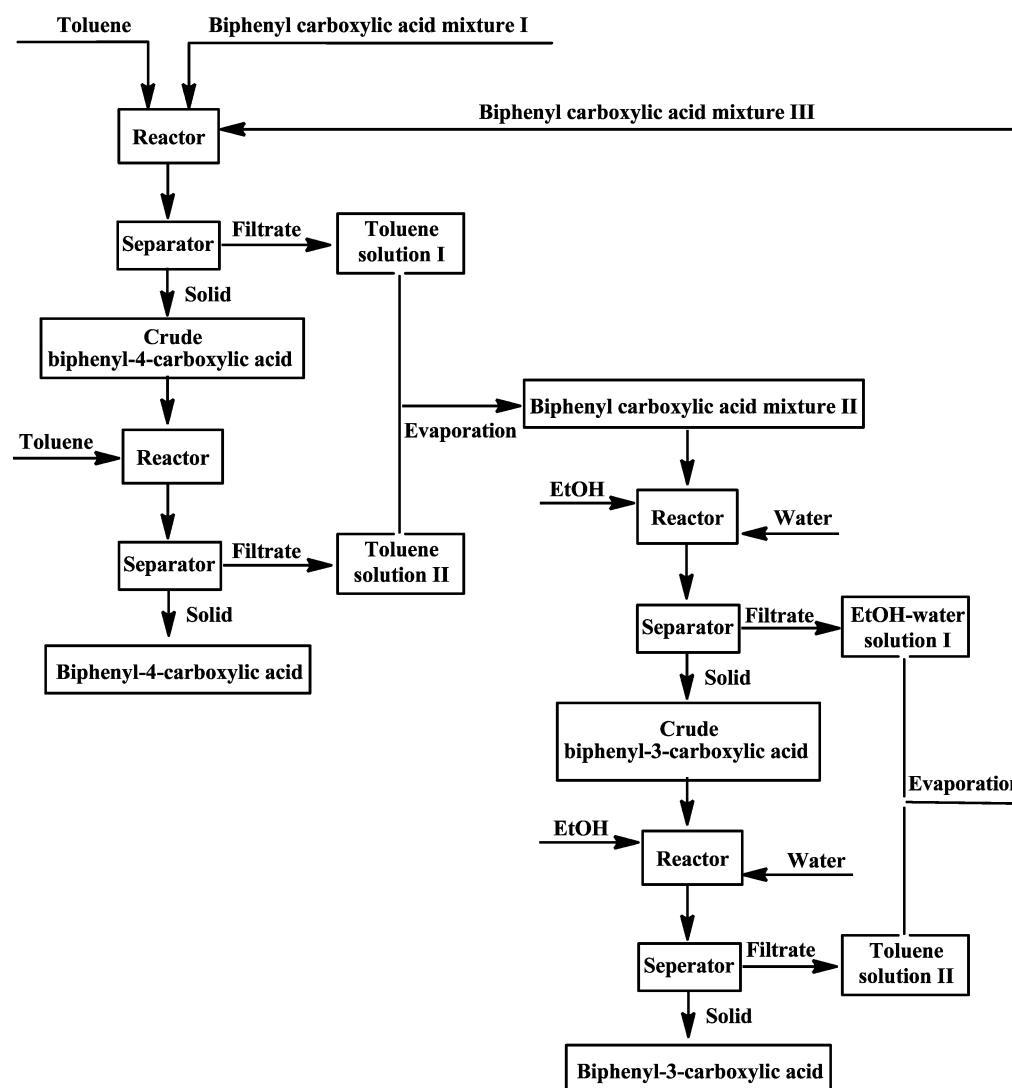


Figure 4. Process flow diagram of separation of the isomers of biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid.

component contains around 100 compounds as revealed by a LC-MS study. Three compounds with content greater than 5% were identified. The molecular weights of these three compounds were determined to be 196, 198, and 198 with a content of about 6%, 17% and 20%, respectively. Careful separation by preparative liquid chromatography led to the isolation and characterization of 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid. In addition, we isolated 12 other components from the mixture, including 1,2-diphenylethane, stilbene, diphenylmethane, benzophenone, methyl benzoate, acetophenone, benzylbiphenyl, terphenyl, anthrone, anthracene-9,10-dione, 9-fluorenone, and benzyl benzoate.

The yellow solid mixture contains many high boiling aromatic compounds, and further separation by distillation is almost impossible. However, we have found that a similar strategy based on aqueous base extraction/acidification can be successfully applied for the separation and isolation of these three components. The yellow solid mixture was first extracted with aqueous Na_2CO_3 . After acidification of the aqueous extracts, a crude mixture containing mainly biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid with a content of 40% and 45%, respectively, was obtained. The carboxylic

acids extracted from the yellow solid mixture accounted for about 40% of its total weight. Further purification by recrystallization from ethanol and water gave a mixture of biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid in a ratio of approximately 5:6. After the Na_2CO_3 extraction, the solid residue was then treated with aqueous NaOH and another batch of crude product, which accounts for approximately 12% of the total mass of the yellow solid mixture and contains mainly 6H-benzo[c]chromen-6-one (~80%), is obtained. Pure 6H-benzo[c]chromen-6-one could be isolated by recrystallization of the crude product from ethanol and water.

The overall separation protocol described above led to the isolation of biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid in a total yield of 20–26% with a separation efficiency of 54–70%, and the isolation of 6H-benzo[c]chromen-6-one in 3.5–4.5% yield with a separation efficiency was 57–75%. The separation procedure is shown in Figure 3.

Further separation of the isomeric biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid in a highly efficient and cost-effective way proved to be a rather challenging task. Although, in principle, many different approaches can be employed for such a purpose, it quickly became clear that several of them are not practically viable. Separation by distillation based on the

Table 1. Recovering Methods and Yields of 9-Fluorenone, 6H-Benzo[c]chromen-6-one, Biphenyl-3-carboxylic Acid, and Biphenyl-4-carboxylic Acid from Benzoic Acid Industrial Residue

products	initial mass content	recovering methods	purity (%)	separation yield (%)	separation efficiency (%)
9-fluorenone	40% in benzyl benzoate residue	Benzyl benzoate residue was treated using NaOH (aq); the crude 9-fluorenone was purified using recrystallization from ethyl acetate and petroleum ether.	>98	25–30	65–72
biphenyl-3-carboxylic acid	17% in yellow solid mixture	Biphenyl-3 and 4-carboxylic acid mixture was extracted from the yellow solid mixture using NaCO ₃ (aq); the isomers were separated using recrystallization from toluene or a mixture of ethanol and water.	>98	5.5–8	32–41
biphenyl-4-carboxylic acid	20% in yellow solid mixture	Crude 6H-benzo[c]chromen-6-one was extracted from the residue, which was obtained after removing all acids from the yellow solid mixture, using NaOH (aq); then the crude was purified using recrystallization from ethanol.	>98	7–10	35–50
6H-benzo[c]chromen-6-one	6% in yellow solid mixture		>98	3.5–4.6	55–75

difference of their boiling points²⁵ is not likely to be attractive as the boiling points of the two components are very high (392.2 °C for biphenyl-3-carboxylic acid and 373 °C for biphenyl-4-carboxylic acid) and would involve a huge input in energy in order to obtain the required distillation temperature under an attainable reduced pressure. Separation based on adsorption using certain types of materials such as cyclodextrins and calixarenes,^{26,27} or chromatographic techniques including column chromatography, liquid chromatography, and preparative chromatography²⁸ are deemed to be less attractive for a large industrial application. The possibility of pursuing a chemical transformation followed by separation and reconversion to the original compounds²⁹ is also left unconsidered as it is quite unlikely to be successful given the fact that these two compounds are two regioisomers of a carboxylic acid. Therefore, our attention was focused on the more realistic recrystallization, provided that good solvent systems can be found out that would allow the two components to be separated due to their different solubility behaviors.³⁰

After examining the solubility of these two compounds in a variety of solvents, which include water, benzene, toluene, hexane, cyclohexane, petroleum ether, methanol, ethanol, DMF, isopropyl alcohol, methylene chloride, chloroform, ethyl acetate, 1,4-dioxane, and THF, it was discovered that the solubility of biphenyl-3-carboxylic acid in toluene was significantly higher than that of biphenyl-4-carboxylic acid, whereas the latter is much more soluble in ethanol. Thus, we first dissolved the mixture in toluene at 100 °C. Biphenyl-4-carboxylic acid was found to precipitate out upon cooling. A pure product is obtained after another recrystallization from toluene.

The remaining residual mixture obtained from the combined mother liquor was then dissolved in a mixture of ethanol and water at reflux temperature. After cooling to room temperature, biphenyl-3-carboxylic acid precipitates out. The crude biphenyl-3-carboxylic acid can be further recrystallized to pure form from ethanol and water. As a result, the total yield of the isolated biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid in one cycle was 60–70%. The yield of biphenyl-4-carboxylic acid was 35–40%, corresponding to a separation efficiency of 62–72%, and the yield of biphenyl-3-carboxylic acid was 25–30%, corresponding to a separation efficiency of >55–65%. The recrystallization method following this protocol has the inherent advantages of being operationally simple, highly efficient, and cost-effective. It should also be pointed out that the solvents used, toluene and ethanol, can be conveniently recyclable and reused, making it an ideal method for industrial production. The process flow diagram is showed in Figure 4.

After establishing the optimized conditions for the isolation and separation of 9-fluorenone, 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid from the benzoic acid industrial residues, we conducted a large scale separation. The separation conditions and relevant processing parameters for this scaleup study, optimized for 10 kg raw materials in a 100 L ceramic reactor, are summarized in Table 1. The final yield of 9-fluorenone from 10.0 kg of the benzyl benzoate residue was 25–30%, and the separation efficiency was about 65–72%. The final separation yield of 6H-benzo[c]chromen-6-one from 10.0 kg of the yellow solid mixture was 3.5–4.6%, and the separation efficiency was 55–75%. The final separation yield of biphenyl-3 and 4-carboxylic acids mixture from the 10.0 kg raw material was 20–25%. and the separation efficiency was 55–72%. The separation conditions and relevant processing parameters of 2.5 kg of biphenyl-3 and 4-carboxylic acid mixture in a 50 L volume glass reactor were also optimized. The final yield of biphenyl-3-carboxylic acid was 25–31%, and the separation efficiency was 50–62%. The yield of biphenyl-4-carboxylic acid was 33–41%, and the separation efficiency was 58–70%. The purity of all the final products isolated, including 9-fluorenone, 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid was in excess of 98%.

We also evaluated the potential environmental impact of our scaleup study. The reagents we used were only NaOH, Na₂CO₃, and HCl, and no other toxic organic materials or metal salts were involved. The organic solvents we used, including petroleum ether (PE), ethyl acetate (EA), toluene, and ethanol, were all recycled in an efficiency of 85% (±5%), 88% (±6%), 90% (±4%), and 82% (±5%), respectively. Therefore, there was minimal loss of reagents in this separation method. Analysis of the wastewater discharged from our scaleup experiment showed that it contains no hazardous materials or pollution and is in accordance with the emission standard of relevant environment regulations.³¹

In addition, we made a cost analysis based on our scaleup separation study. The raw materials, including the benzyl benzoate residue and the yellow solid mixture, are all chemical wastes and obtained free of acquisition cost. To obtain 1 ton of 9-fluorenone, 0.7 ton of sodium hydroxide, 0.4 ton of ethyl acetate, and 0.5 ton of petroleum ether are needed. On the basis of the current price (Chinese chemical market) of sodium hydroxide (\$320/ton), ethyl acetate (\$1100/ton), and petroleum ether (\$900/ton), the cost for the production of 1 ton 9-fluorenone is about \$2320.³² Additional cost includes water, power, and human labor, bringing the total to \$3000 per ton of product. This number may differ regionally. However,

the traditional production process of 9-fluorenone from the oxidation of 9H-fluorene³³ would cost more than \$8000/ton based on the current price of 9H-fluorene, which is about \$5000/ton in the Chinese industrial chemicals market. Therefore, the economic benefit for recycling 9-fluorenone from the benzoic acid industrial residues is very high. The current price of biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid is about \$20,000/ton and \$50,000/ton, respectively. The total cost for sodium carbonate, hydrochloric acid, sodium hydroxide, toluene, and ethanol that were used in the recycling of these two chemicals is very low when compared to the prices of the two biphenyl carboxylic acids. The recovery cost for each product was estimated to be less than \$8000/ton. On the other hand, chemical synthesis of biphenyl-3-carboxylic acid or biphenyl-4-carboxylic acid according to the currently production technology^{23,24,34} involves the Pd-catalyzed Suzuki coupling between 3-bromobenzoic acid or 4-bromobenzoic acid, phenylboronic acid in the presence of a base in organic solvents. Large scale industrial application of this synthesis is not likely to be practical due to the high cost of the boronic acid and the transition metal catalyst. Application in the pharmaceutical and medicinal industry is also limited due to separation challenges and toxicity concerns of the catalyst. As a result, separating these biphenyl carboxylic acids from benzoic acid production waste is also very meaningful.

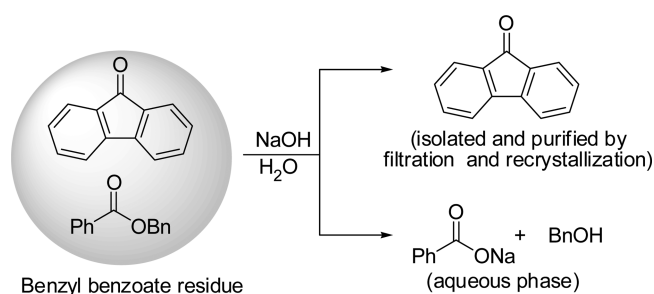
CONCLUSION

In conclusion, we have developed a new method to obtain 9-fluorenone, 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid from benzoic acid industrial residues using inexpensive alkalis (NaOH and Na₂CO₃) and an acid (HCl). The separation can be performed with very simple procedures to afford these chemicals in high yields and purities. The organic solvents that were used during recrystallization can be recycled and reused. A scaleup study employing this method was also conducted to demonstrate its advantages of being both cost effective and environmentally friendly. Further studies of recovering aromatic compounds from other related industrial wastes are underway.

EXPERIMENTAL SECTION

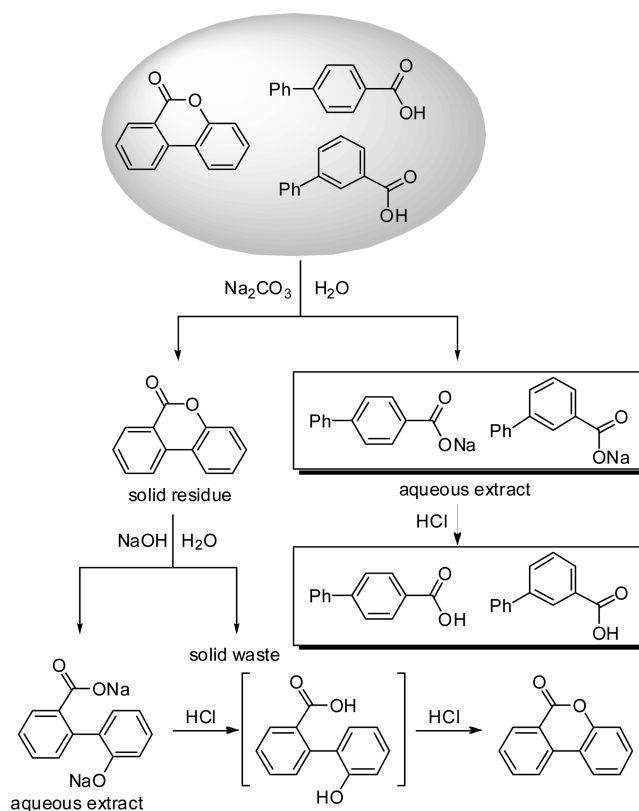
General. NaOH (pellets), Na₂CO₃ (pellets), HCl (35%), and all organic solvents, including ethanol, methanol, isopropyl alcohol, ethyl acetate, petroleum ether, methylene chloride, chloroform, benzene, toluene, THF, DMF, hexane, cyclohexane, and 1,4-dioxane, were purchased from Tianjin Chemical Co. All chemical reagents were of analytical grade and used as received. Benzoic acid industrial waste came from the Shijiazhuang Chemical Fiber Co., Ltd. in China. IR spectra were recorded on a Shimadzu 8400-S spectrometer (wave numbers in cm⁻¹). Nuclear magnetic resonance (NMR) spectra were recorded on a Bruker DRX 300 MHz or a Bruker AVII 400 MHz NMR spectrometer using CDCl₃ or acetone-*d*₆ as solvent; chemical shifts are expressed in parts per million (δ scale) downfield from tetramethylsilane (δ 0.00 ppm). Data are presented as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet and/or multiple resonances), and coupling constants are in Hertz (Hz).

Representative Procedure for the Separation of 9-Fluorenone from the Benzyl Benzoate Residue in Lab-Scale. A sample of the benzyl benzoate residue (100 g) containing 39.2% 9-fluorenone, 10.8% benzyl benzoate, NaOH (20 g, 0.50 mol), and water (500 mL) was placed in a 1000 mL three-necked flask equipped with a mechanical stirrer and a condenser and stirred at reflux temperature for 2 h. After cooling to room temperature, the solid was filtered and washed with water to give 36.5 g of crude 9-fluorenone, which is 88.6%



pure. Further purification by recrystallization in ethyl acetate and petroleum ether (8:3 v/v) afforded 29.2 g (0.162 mol) pure 9-fluorenone as yellow crystals, mp 83–85 °C. Separation yield: 29.2%. Separation efficiency: 74.5%. ¹H NMR (300 MHz, CDCl₃): δ 7.65 (d, *J* = 7.2 Hz, 2H), 7.45–7.50 (m, 4H), 7.26–7.32 (m, 2H). ¹³C NMR (75.5 MHz, CDCl₃): δ 193.6, 144.3, 134.5, 134.0, 128.9, 124.0, 120.2.³³

Representative Procedure for Separation of 6H-Benzo[c]-chromen-6-one and Biphenyl-3- and Biphenyl-4-Carboxylic



Acids Mixture from Yellow Solid Mixture in a Lab-Scale. A sample of the yellow solid mixture (100 g) containing 6.1% 6H-benzo[c]chromen-6-one, 17.2% biphenyl-3-carboxylic acid, 21.6% biphenyl-4-carboxylic acid, Na₂CO₃ (20 g, 0.19 mol), and water (500 mL) was placed in a 1000 mL three-necked flask equipped with a mechanical stirrer and a condenser. The reaction mixture was stirred at reflux temperature for 2 h. After cooling to room temperature, the aqueous solution was separated from the insoluble material by filtration. The filtrate was then acidified with 35% HCl. The precipitates were filtered, washed with water, and dried to give 39.8 g of crude mixture of the acid products. Purification of the crude acids by recrystallization in ethanol and water (4:1 v/v) afforded 26.5 g of a mixture as white solid containing biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid in a ratio of a 5:6. Total separation yield: 28.5%. Separation efficiency: 73.5%.

The solid residue from the above Na₂CO₃ extraction experiment was placed in a 1000 mL three-necked flask equipped with a

mechanical stirrer and a condenser and treated with NaOH (5 g, 0.125 mol) and water (250 mL). The reaction mixture was then heated to reflux under stirring for 1 h. After cooling to room temperature, any insoluble residue was filtered off, and the clear filtrate was acidified with 35% HCl. After the putative phenolic acid intermediate was found to be completely converted to the lactone product in the acidic conditions, 6.8 g crude solid was obtained after filtration and drying. Purification by recrystallization in ethanol and water (4:1 v/v) afforded pure 3.50 g (0.0179 mol) 6H-benzo[c]chromen-6-one as white solid. Separation yield: 3.50%. Separation efficiency: 57.4%. IR (KBr, ν/cm^{-1}): 3078, 1734, 1607, 1501, 1457, 745, 721, 682. ^1H NMR (300 MHz, CDCl_3): δ 8.28 (d, $J = 8.0$ Hz, 1H), 7.98 (d, $J = 7.6$ Hz, 1H), 7.92 (d, $J = 8.0$ Hz, 1H), 7.71 (t, $J = 7.6$ Hz, 1H), 7.47 (t, $J = 7.6$ Hz, 1H), 7.37 (t, $J = 8.0$ Hz, 1H), 7.19–7.27 (m, 1H). ^{13}C NMR (75.5 MHz, CDCl_3): δ 161.1, 151.2, 134.8, 134.7, 130.5, 130.4, 128.8, 124.5, 122.7, 121.6, 121.2, 117.9, 117.7.³⁵

Representative Procedure for the Separation of Biphenyl-3-carboxylic Acid and Biphenyl-4-carboxylic Acid in a Lab-Scale.

The carboxylic acids mixture thus obtained (26.5 g) and toluene (300 mL) were placed in a 1000 mL three-necked flask equipped with a mechanical stirrer and a condenser, and stirred at 80 °C for 0.5 h before cooled to room temperature. Separation by filtration give 9.8 g of crude biphenyl-4-carboxylic acid and toluene solution I enriched in biphenyl-3-carboxylic acid. The crude biphenyl-4-carboxylic acid (11.3 g) was recrystallized again in toluene (150 mL) by heating to 120 °C for 10 min in a 500 mL three-necked flask equipped with a mechanical stirrer and a condenser. After cooling to 40 °C and rapid filtration at this temperature, 10.1 g (0.510 mol) of pure biphenyl-4-carboxylic acid was obtained as white solid. Separation yield: 38.1%. Separation efficiency: 69.9%. Mp 226–228 °C. ^1H NMR (400 MHz, acetone- d_6): δ 8.12 (d, $J = 8.4$ Hz, 2H), 7.81 (d, $J = 8.4$ Hz, 2H), 7.75 (d, $J = 7.2$ Hz, 2H), 7.52 (d, $J = 7.2$ Hz, 2H), 7.40–7.46 (m, 1H). ^{13}C NMR (100 MHz, acetone- d_6): δ 167.01, 145.21, 139.74, 130.18, 129.59, 129.16, 128.40, 127.07, 126.87.^{23,24} The resulting toluene filtrate was then combined with toluene solution I from the first recrystallization and concentrated to give 16.4 g of a new biphenyl carboxylic acids mixture. This mixture was then placed in ethanol (300 mL) and water (250 mL) in a 1000 mL three-necked flask equipped with a mechanical stirrer and a condenser and stirred at reflux temperature for 1 h before cooled to room temperature. Separation by filtration gave crude biphenyl-3-carboxylic acid (8.9 g). The crude biphenyl-3-carboxylic acid was recrystallized from ethanol (200 mL) and water (180 mL) to give 7.1 g (0.036 mol) of pure biphenyl-3-carboxylic acid as a white solid. Separation yield: 26.8%. Separation efficiency: 58.9%. Mp 165–167 °C. ^1H NMR (400 MHz, acetone- d_6): δ 8.30 (s, 1H), 8.04 (d, $J = 7.6$ Hz, 1H), 7.92 (d, $J = 7.6$ Hz, 1H), 7.72 (d, $J = 7.6$ Hz, 2H), 7.63 (t, $J = 7.6$ Hz, 1H), 7.52 (t, $J = 7.6$ Hz, 2H), 7.42 (t, $J = 7.4$ Hz, 1H). ^{13}C NMR (100 MHz, acetone- d_6): δ 167.08, 141.24, 139.94, 131.46, 131.24, 129.60, 129.04, 128.19, 127.81, 127.08, 126.91.³⁶

Examples for Pilot Scale Separation of 9-Fluorenone, 6H-Benzo[c]chromen-6-one, and Biphenylcarboxylic Acids. Separation of 9-Fluorenone from Benzyl Benzoate Residue. Benzyl benzoate residue (10.0 kg) containing 39.2% 9-fluorenone, 10.8% benzyl benzoate, NaOH (2.0 kg, 50 mol), and water (50 L) was placed in a 100 L ceramic reactor (Jiangsu Yang-Yang Chemical Manufacturing Company, Ltd., China) with a mechanical stirrer and a condenser and stirred at reflux temperature for 3 h. After cooling to room temperature, the reaction mixture was filtered, washed with water, and dried to give 3.28 kg of the crude 9-fluorenone, which is 89.2%. Recrystallization in ethyl acetate and petroleum ether (8:3 v/v) afforded 2.69 kg (15.6 mol) pure product as yellow crystals. Separation yield: 26.9%. Separation efficiency: 68.6%.

Separation of 6H-Benzo[c]chromen-6-one, Biphenyl-3-carboxylic Acid, and Biphenyl-4-carboxylic Acid from Yellow Solid Mixture. The yellow solid mixture (10.0 kg) containing 6.1% 6H-benzo[c]chromen-6-one, 17.2% biphenyl-3-carboxylic acid, 21.6% biphenyl-4-carboxylic acid, Na_2CO_3 (2.0 kg, 19 mol), and water (50 L) was placed in a 100 L ceramic reactor equipped with a mechanical stirrer and a condenser and stirred at reflux temperature for 2 h. The reaction mixture was stirred at reflux temperature for 2 h. After cooling to room

temperature, the aqueous solution was separated from the insoluble material by filtration. The filtrate was then acidified with 35% HCl. The precipitates were filtered, washed with water, and dried to give 3.76 kg of crude mixture of biphenyl-3-carboxylic acid biphenyl-4-carboxylic acid. Further purification by recrystallization from ethanol and water (4:1 v/v) afforded 2.58 kg of the mixed products. The ratio of biphenyl-3-carboxylic acid and biphenyl-4-carboxylic acid was 5.1:6.2. The solid residue was treated with NaOH (0.50 kg, 12.5 mol) and water (25 L) in a 100 L ceramic reactor equipped with a mechanical stirrer and a condenser, and the reaction mixture was stirred at reflux temperature for 1 h. After cooling to room temperature, insoluble residues were filtered off, and the clear filtrate was acidified with 35% HCl. After filtration, 656 g of the crude product was obtained after drying. Further purification by recrystallization in ethanol and water (4:1 v/v) afforded 326 g (1.66 mol) pure 6H-benzo[c]chromen-6-one as a white solid. Separation yield: 3.26%. Separation efficiency: 53.4%.

The mixed acid products (2.58 kg) from the above experiment and toluene (30 L) were placed in a 100 L ceramic reactor equipped with a mechanical stirrer and a condenser, and the resulting mixture stirred at 80 °C for 0.5 h before cooling to room temperature. After separation by vacuum filtration, 965 g of the crude biphenyl-4-carboxylic acid and toluene solution I was obtained. The crude product and toluene (15 L) were then placed in a 100 L ceramic reactor equipped with a mechanical stirrer and a condenser. After stirring at 120 °C for 30 min, the hot solution was cooled to 40 °C and filtered at this temperature to give 916 g (4.62 mol) of the pure biphenyl-4-carboxylic acid as a white solid and toluene solution II. Final separation yield: 9.2%. Final separation efficiency: 42.4%.

The toluene solutions I and II were combined and concentrated to give 1.664 kg of new acid product mixture. The mixture was then recrystallized from ethanol (30 L) and water (25 L) to give 869 g of the crude biphenyl-3-carboxylic acid. Further purification by recrystallization from ethanol (20 L) and water (18 L) afforded 672 g (3.39 mol) of pure biphenyl-3-carboxylic acid as a white solid. Final separation yield: 6.72%. Final separation efficiency: 39.1%.

■ ASSOCIATED CONTENT

📄 Supporting Information

Figure S1: ^1H and ^{13}C NMR spectra of 9-fluorenone (in CDCl_3). Figure S2: HPLC trace of 9-fluorenone. Figure S3: FTIR, ^1H and ^{13}C NMR, COSY, and DEPT spectra of 6H-benzo[c]chromen-6-one. Figure S4: ^1H and ^{13}C NMR spectra of biphenyl-3-carboxylic acid. Figure S5: HPLC trace of biphenyl-3-carboxylic acid. Figure S6: ^1H and ^{13}C NMR spectra of biphenyl-4-carboxylic acid. Figure S7: HPLC trace of biphenyl-4-carboxylic acid. Figure S8: LC-MS analytical report of yellow solid mixture. Table S1: Waste water analytical reports for separating pure 9-fluorenone from the benzyl benzoate residue (originals given in Chinese are followed by English translation). Table S2: Waste water analytical reports for separating 6H-benzo[c]chromen-6-one, biphenyl-3-carboxylic acid, and biphenyl-4-carboxylic acid mixture from the yellow solid mixture (originals given in Chinese are followed by English translation). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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