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Sustainable Material Management of Industrial Hazardous Waste in Taiwan: Case Studies in Circular Economy

Chi-Hung Tsai [1], Yun-Hwei Shen [1] and Wen-Tien Tsai [2,*]

[1] Department of Resources Engineering, National Cheng Kung University, Tainan 701, Taiwan; ap29fp@gmail.com (C.-H.T.); yhshen@mail.ncku.edu.tw (Y.-H.S.)
[2] Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung 912, Taiwan
* Correspondence: wttsai@mail.npust.edu.tw; Tel.: +886-8-7703202

Abstract: In recent years, the rapid economic development in Taiwan has resulted in greater complexity in handling industrial hazardous waste. The main aim of this paper was to present a trend analysis of the online reported amounts of industrial hazardous waste from the official database over the past decade (2010–2020). In addition, this study focused on the environmental policies and regulatory measures for the mandatory material resources from industrial hazardous waste according to the promulgation of the revised Waste Management Act. It was found that the annual reported amounts of industrial hazardous waste ranged from 1200 thousand metric tons to 1600 thousand metric tons, reflecting a balanced relationship between the industrial production and waste management. Based on the principles of resource recycling and circular economy, some case studies for specific types of industrial hazardous waste (including spent acid etchant, spent pickling liquid, and spent dimethyl formamide-contained liquid) were compiled to echo the government efforts in sustainable material management. In Taiwan, recycling amounts in 2020 were recorded up to 92,800, 130,460, and 54,266 metric tons, respectively. It was suggested to be a successful circular economy model in the printed circuit boards, steel/iron processing, and synthetic leather industries. In order to effectively reduce the environmental loadings and conserve material resources from industrial hazardous waste, some recommendations were also addressed to provide for the policy makers, environmental engineers and process manager.

Keywords: industrial hazardous waste; sustainable material management; environmental policy; regulatory measure; Taiwan

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1. Introduction

The term hazardous waste refers to any solid, semisolid, or liquid that poses a significant threat to human health and environment risks due to its toxicity characteristics and hazardous constituents. The term industrial hazardous waste means that it is generated from industry activities such as industrial processes, mining, medical services, public services (e.g., waste incineration plant, waste recycling plant), and so on. However, nuclear waste or radioactive waste is a special IHW that is not scoped by the relevant waste management regulations in the developed countries [1]. According to the Resource Conservation and Recovery Act (RCRA) [2], hazardous waste has been defined as being either a listed hazardous waste or a characteristic hazardous waste. The former is one that appears on the list of hazardous and/or toxic substances, which were identified by the US Environmental Protection Agency (EPA). They include the hazardous waste from nonspecific sources (EPA waste number coded by "F"), the hazardous waste from specific sources (EPA waste number coded by "K"), the acutely hazardous commercial chemical products and manufacturing chemical intermediates (EPA waste number coded by "P"), and toxic commercial chemical products and manufacturing chemical intermediates (EPA waste number coded by "U") [1]. If a waste does not appear on the list of hazardous waste, it may still be identified as a hazardous waste based on its test of toxicity characteristics leaching procedure (TCLP). This rigorous definition is indicated by the fact that hazardous waste management is a serious issue pertaining to health and environmental risks if badly managed [3].

In Taiwan, industrial waste is basically divided into "general industrial waste" and "industrial hazardous waste" (IHW) based on the Waste Management Act (WMA). Herein, the industrial waste generators may include (1) industrial, agricultural, and mining plants and sites; (2) construction and building enterprises; (3) medical service organizations (hospitals); (4) public and private waste clearance, treatment, and disposal organizations (e.g., waste incineration plants, scrap car treatment plant); (5) laboratories of schools, agencies, and groups; and (6) other enterprises designated by the central competent authority (i.e., Environmental Protection Administration, EPA). According to the definition of IHW by the regulation ("Standards for Defining Industrial Hazardous Waste"), it is similar to that of the RCRA. In Taiwan, IHW was determined by the regulated list and the hazardous characteristics [4]. The former includes "manufactured hazardous industrial waste", "scrap mixed metal", and "biomedical and infectious waste". Before the Taiwan government revised the WMA in 1999, some events of illegal dumping of IHW and its transboundary movement have caused serious environmental impacts and scandals [5–7], which were also found in other Asian countries [8,9]. To efficiently reduce IHW generation and its potential risks after treatment and disposal, the EPA revised the act in 1999 and formed a regulatory framework for industrial waste management [10,11]. Since 2000, the EPA further established the "National Industrial Waste Management Program" and the "Industrial Waste Control Center", as well as a tracking system that tracks the life cycle of industrial waste from its generation source to final disposal [12].

In recent years, a circular economy has been adopted as a new business model, which aims at transforming the traditional (linear) economic model into a recyclable and regenerative system [13]. Furthermore, this model can alleviate the impact of coronavirus disease (COVID-19) outbreak on supply chains and food systems between the consumption–production (or customer–supplier) relationships [14,15]. For example, the recovery of precious metals from waste printed circuit boards (WPCB) embedded in waste electrical and electronic equipment (WEEE) can be economically sustainable using economic feasibility analysis [16]. In the previous study [17], it presented the status of industrial waste generation and treatment during the years of 2010–2020 and the promotion policies and regulatory measures for the mandatory non-hazardous renewable resources from industrial sources in Taiwan. Because there is little discussion about Taiwan's IHW recycling (or reuse) in the literature survey using Web of Science, this paper further analyzed the trends of IHW generation and treatment during the period of 2010–2020. Furthermore, the Taiwan EPA policies for sustainable material management of industrial waste were addressed to step on international trends. Finally, the regulatory promotion for the IHW recycling (or reuse) was refined to echo the circular economy by the case studies of three IHW items, including spent acid etchant, spent pickling liquid, and spent dimethyl formamide (DMF)-contained liquid.

2. Data Mining

As mentioned above, the main purposes of this study were to analyze the updated status of IHW management (i.e., reported generation amounts and treatment methods) and further address the environmental policies and regulatory measures for promoting IHW recycling (or reuse), as well as the case studies in the sustainable material management of three IHW items. Therefore, this work was based on the data mining of statistical databases and regulatory measures relevant to the IHW recycling (or reuse), which will be briefly stated as follows:

- Baseline information in the reported amounts of IHW generation and treatment

The updated data on the statistics of IHW generation and treatment in Taiwan were obtained from the official yearbook [18,19] and accessed on the website [20], which was established by the EPA.

- Environmental policies and regulatory measures for promoting IHW recycling (or reuse)

To focus on the IHW recycling (or reuse) in Taiwan, the information about the environmental policies and regulatory measures for these issues were accessed on the EPA website concerning sustainable material management [21] and the official laws and regulations website [22], which was established by the Ministry of Justice (MOJ).

- Case studies in the IHW recycling (or reuse)

To echo the IHW recycling (or reuse), three case studies on spent acid etchant, spent pickling liquid, and spent dimethyl formamide (DMF)-contained liquid were exampled by accessing them on the Industrial Waste Recycling Information Network [23], which was sponsored by the Industrial Development Bureau of the Ministry of Economic Affairs (MOEA).

3. Results and Discussion

3.1. Trend Analysis of Industrial Hazardous Waste Generation and Treatment

3.1.1. Industrial Hazardous Waste Generation

Based on the database established by the central competent authority (i.e., EPA) [20], Table 1 lists the reported generation amounts of general industrial waste and IHW during the period of 2010–2020 [18–20]. Figure 1 shows the variations in the reported amounts of IHW generation. Notably, the average percentage of IHW accounted for about 7.2% based on the total amounts of industrial waste generation, ranging from 6.41% to 8.51%. The reported amounts indicated a fluctuated variation from about 1.2 million metric tons in 2011 to a peak record of approximately 1.6 million metric tons in 2014. Thereafter, the reported amounts showed a slight variation, which can be attributable to the progressive implementation of industrial waste minimization (including source reduction and waste recycling and reuse) in the industrial sector, thus retarding the expected increase in IHW generation in recent years. For example, Taiwan's printed circuit board (PCB) manufacturing industry contributed a significant supply chain globally, but the reported amounts of spent acid etchant indicated a decreasing trend. This case study will be presented in Section 3.4.

According to the WMA, the categories (or codes) of IHW in Taiwan can be grouped into the following types:

- A-type: Manufactured hazardous industrial waste.
- B-type: Industrial waste containing toxic chemical substances.
- C-type: Biomedical, infectious, and industrial waste identified by TCLP.
- E-type: Scrap mixed metal.
- R-type: Including spent acid etchant, spent pickling liquid, spent DMF-contained liquid, and spent developer/fixer liquid.

Figure 2 depicts the percentages of five IHW types in 2020 based on the reported amounts [19], which indicated the order as follows: C-type (780,005 metric tons, 51.20%) > A-type (407,595 metric tons, 26.75%) > R-type (277,900 metric tons, 18.24%) > E-type (55,555 metric tons, 3.65%) > B-type (2421 metric tons, 0.16%).

Table 1. Reported amounts of industrial waste generation during the period of 2010–2020 in Taiwan [1].

Year	Industrial General Waste	Industrial Hazardous Waste	Total
2010	16,868,135 (93.24%)	1,223,113 (6.76%)	18,091,249 (100.00%)
2011	17,532,693 (93.59%)	1,201,079 (6.41%)	18,733,773 (100.00%)
2012	16,696,197 (93.04%)	1,249,532 (6.96%)	17,945,729 (100.00%)
2013	17,226,486 (92.25%)	1,447,705 (7.75%)	18,674,192 (100.00%)
2014	17,235,907 (91.49%)	1,603,661 (8.51%)	18,839,568 (100.00%)
2015	17,788,805 (92.84%)	1,371,887 (7.16%)	19,160,692 (100.00%)
2016	17,615,673 (92.85%)	1,357,365 (7.15%)	18,973,038 (100.00%)
2017	17,923,113 (92.54 %)	1,444,014 (7.46%)	19,367,127 (100.00%)
2018	20,716,321 (93.41%)	1,461,746 (6.59%)	22,178,067 (100.00%)
2019	18,449,869 (92.99%)	1,390,642 (7.01%)	19,840,511 (100.00%)
2020	18,506,938 (92.39%)	1,523,476 (7.61%)	20,030,414 (100.00%)

[1] Sources [18–20]; unit: metric ton.

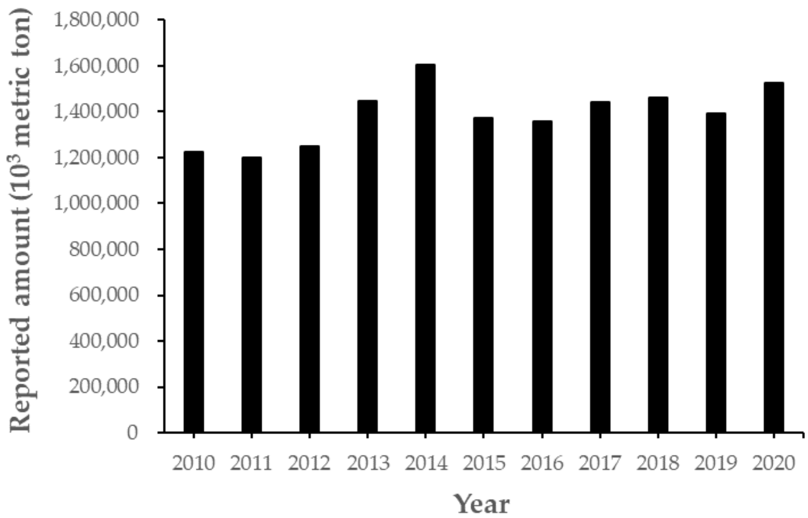

Figure 1. Variations of industrial hazardous waste generation in 2010–2020.

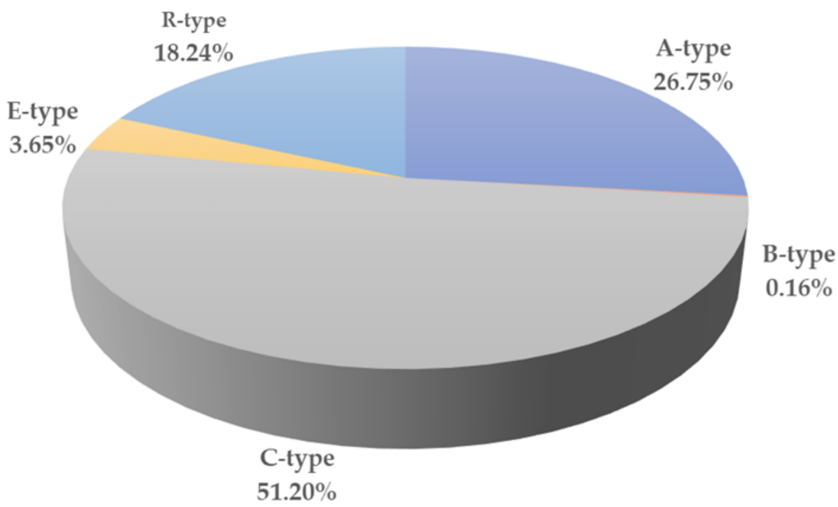

Figure 2. Pie chart of categories of industrial hazardous waste generation in 2020.

3.1.2. Industrial Hazardous Waste Treatment

As mentioned above, the WMA is the foundation for industrial waste management in Taiwan. According to the regulation ("Methods and Facilities Standards for the Storage, Clearance and Treatment of Industrial Waste"), the term "treatment" refers to the three methods, including immediate treatment (e.g., incineration, distillation), final disposal (e.g., sanitary landfill), and recycling (or reuse). Concerning the IHW recycling (or reuse), it is defined as "raw material, materials, fuel, or other recycling (or reuse) methods recognized by the central industry competent authority via self-use, sale, transfer, or commissioning, and in compliance with the related regulations". Table 2 summarizes the reported amounts of IHW treatment during the period of 2010–2020 [18–20]. Figure 3 further depicts the corresponding percentages of IHW treatment approaches by recycling (or reuse), self-treatment, commissioned/joint treatment, and exported treatment in 2020. Under the promotions of circular economy [24] and sustainable material management [25–27] by the EPA and the Ministry of Economic Affairs (MOEA), it showed that the amounts of IHW recycling (or reuse) indicated an increasing trend from 684,978 metric tons in 2010 to 952,159 metric tons in 2020, reaching a recycling (or reuse) rate of over 62%.

Table 2. Reported amounts of industrial hazardous waste treatment during the period of 2010–2020 in Taiwan [1].

Year	Reuse	Self-Treatment	Commissioned or Joint Treatment	Exported Treatment
2010	684,978	69,140	468,079	18,772
2011	708.841	51,739	539,384	19,141
2012	729,783	51,290	558,544	20,568
2013	747,083	233,315	541,782	41,379
2014	764,217	292,152	579,092	41,950
2015	727,200	79,626	584,311	40,336
2016	738,997	57,210	584,691	10.828
2017	799,464	73,373	554,616	10,285
2018	933,477	110,103	429,326	5017
2019	885,816	138,305	389,113	3703
2020	952,159	147,953	409,256	4953

[1] Sources [18–20]; unit: metric ton.

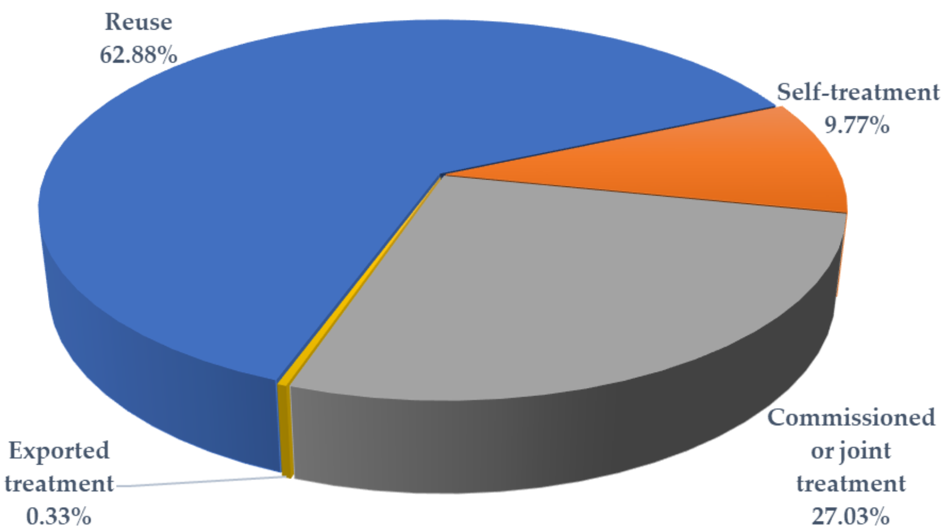

Figure 3. Pie chart of processing methods of industrial hazardous waste treatment in 2020.

3.2. Environmental Policies for Sustainable Material Management of Industrial Waste

With the revision of the WMA [22], the Taiwan government has established a sustainable material management of industrial hazardous waste over the past two decades. In 1999, the central competent authority (i.e., EPA) revised the act to establish the legal frameworks for industrial waste treatment methods and their incentives and penalties, thus focusing on the waste reuse. Since 2000, the EPA further formulated the "National Industrial Waste Management Program", including the establishment of the "Industrial Waste Control Center", an electronic tracking system as well as an online reporting system that controls the complete life cycle of industrial wastes from generation source to final disposal. The program and statutory penalties were originally set to manage the industrial waste flow and eliminate illegal dumping. Consequently, the industrial waste generators were forced to adopt the environmental policies for industrial waste reuse and recycling. According to the official report [19], the percentage of industrial waste recycling (or reuse) was about 84.6% in 2020. To promote the industrial waste recycling (or reuse), this issue shall be processed in accordance with the regulations based on Article 39 of the act, which was stipulated by the central industry competent authorities (e.g., MOEA) or central competent authority (i.e., EPA). Therefore, the central industry competent authorities shall be in consultation with the EPA for announcing IHW items that must be recycled or reused, according to the relevant regulations.

In review of international trends in sustainable material management (SMM) initiated by the Organization for Economic Cooperation and Development (OECD) since the mid-2000s [25–27], the EPA set the resource circulation policy, which focused on the sustainable resource management in replacement of traditional waste management. The vision of this SMM policy was to keep resource sustainability in mind and to create a new society for resource circulation and utilization in life. Its main goals were to maximize resource utilization efficiency and minimize environmental impact and influences. In this regard, the promotion was set into the two following stages [21]:

- In short term

It will be targeted at industrial waste items and materials/products of which statistical data are available. In addition, the government participated and promoted the idea of SMM in the way of partnership, helping the industrial waste generators to meet the goals of material conservation, waste reduction, and waste reuse and recycling.

- In long term

Through inter-ministerial promotion and industrial sector's participation, the EPA proposed the relevant indicators (e.g., resource productivity, cyclic use rate) to expand the benefits of SMM. Taiwan's SMM policy can step on the progress in OECD resource sustainability policy.

3.3. Regulatory Measures for Industrial Hazardous Waste Recycling

In Taiwan, the regulatory measures for industrial hazardous waste recycling are based on the "Methods and Facilities Standards for the Storage, Clearance and Treatment of Industrial Waste", the "Management Regulations on the Reuse of Industrial Waste under the Supervision by the Ministry of Economic Affairs", and the "Management Regulations on the Reuse of Industrial Waste under the Supervision by the Ministry of Health and Welfare" under the authorization of the WMA. Some case studies in IHW recycling will be addressed in Section 3.4 to echo the policies for sustainable material management.

In order to connect with IHW recycling and reuse, the relevant measures, including technological guidelines and administrative management, have been incorporated into these regulations, which will be briefly summarized as follows:

- The treatment methods include the categories of intermediate treatment, final disposal, and reuse. In the intermediate treatment methods for IHW reuse or recycling, they can refer to the physical separations such as distillation, extraction, evaporation, and membrane separation. For example, distillation systems can be applied for recovering available materials from spent solvents or spent acid/base liquids.

- In the reuse methods, it refers to the use of IHW as raw material, fuel, or other acts of use recognized by the central industry competent authority via self-reuse, commissioning, or joint reuse in compliance with the reuse regulations. In this regard, some IHW types have been listed on the reuse lists (R-25), including spent acid etchant, spent pickling liquid, spent DMF-contained liquid, spent developer/fixer liquid, and spent mixed solvent. In Taiwan, the reuse of spent developer/fixer liquid as a raw material for silver-based products should be managed by the central industry competent authority (i.e., Ministry of Health and Welfare). Other above R-25 lists are regulated by the central industry competent authority (i.e., Ministry of Economic Affairs).
- Concerning the administrative applications for approving the reuse of IHW, it can be conducted based on the specified methods, which will be announced by the central industry competent authority. In addition, the reuse of IHW can be conducted based on the approval by the EPA. Those not listed in the previous two provisions may be individually applied by joint venture of IHW generators and recycling enterprises for approval by the EPA and can then come into legal reuse.

3.4. Case Studies of Industrial Hazardous Waste Recycling

As mentioned above, there are some types of IHW that shall be requested to recover hazardous and/or available materials from them under the authorization of the WMA. The compulsory IHW for recycling included spent acid etchant, spent pickling liquid, spent DMF-contained liquid, and spent developer/fixer liquid. These resources were categorized into the R-type waste in the R-25 group. Among them, the reported amounts of spent developer/fixer liquid ranged from 2 to 14 metric tons per year, which were much smaller than those of the other three IHW. Table 3 lists the reported amounts of spent acid etchant, spent pickling liquid, and spent DMF-contained liquid during the period of 2010–2020 in Taiwan [20]. The data on the spent acid etchant and spent DMF-contained liquid indicated a decreasing trend but showed a fluctuated variation in the case of spent pickling liquid. These situations can be associated with the changes in Taiwan's industrial structure over the past decade. The following subsections will discuss the case studies in recycling spent acid etchant, spent pickling liquid, and spent DMF-contained liquid.

3.4.1. Spent Acid Etchant

Most of this IHW was generated from the printed circuit board (PCB) manufacturing industry [24]. According to the regulation ("Management Regulations on the Reuse of Industrial Waste under the Supervision by the Ministry of Economic Affairs"), spent acid etchant must contain a copper ion concentration of larger than 50 g/L produced from the etching processes. Its reuse purposes involve the raw materials for acid etchant, ferric chloride ($FeCl_2$), ferrous chloride ($FeCl_3$), polyaluminum chloride, copper (copper powder), copper salts, copper chloride, copper oxychloride, copper carbonate, copper sulfate, copper acetate, copper hydroxide, or cuprous oxide. According to the review by Yu et al. [28], there are various regeneration methods for recycling etchant solutions from PCB industry, finding that the metal recovery approach may be superior to other methods based on its economic and environmental performances. In this regard, various metal recovery approaches have been studied using electrochemical processes [29–32]. Figure 4 shows a basic flowchart of spent acid etchant recycling that has been adopted by the industry in Taiwan. Herein, the aluminum was used as sacrificial metal in cementation processes. The by-product, ferric chloride ($FeCl_3$), can be reused as a coagulant in wastewater treatment plants.

Table 3. Reported amounts of spent acid etchant, spent pickling liquid, and spent DMF-contained liquid in Taiwan [1].

Year	Spent Acid Etchant [2]	Spent Pickling Liquid [3]	Spent DMF-Contained Liquid [4]
2010	131,793	109,971	102,278
2011	122,850	119,729	83,700
2012	114,619	150,512	87,623
2013	112,170	144,044	91,279
2014	114,036	134,305	84,023
2015	106,025	133,509	81,702
2016	101,586	140,261	76,665
2017	101,699	148,889	75,247
2018	97,998	161,074	77,042
2019	88,599	136,892	64,394
2020	92,800	130,460	54,266

[1] Sources [20]; unit: metric ton. [2] Spent liquid with copper ion concentration of larger than 50 g/L produced from the etching processes in the printed circuit board (PCB) industry. [3] Spent liquid with iron ion concentration of larger than 80 g/L from the metal finishing processes in the iron/steel-making industry. [4] Spent liquid with a concentration of less than 30 wt% dimethyl formamide (DMF) from the coating and curing processes of polyurethane (PU) synthetic leather industry.

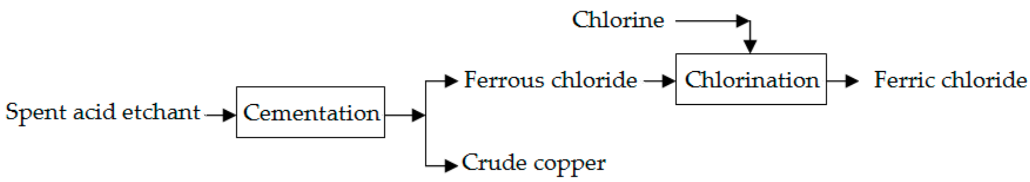

Figure 4. Basic flowchart of spent acid etchant recycling.

3.4.2. Spent Pickling Liquid

This IHW was produced by the industrial surface finishing processes, which involved the use of hydrochloric acid or sulfuric acid solution for pickling iron or steel materials. According to the regulation as mentioned above, spent pickling liquid must contain an iron ion concentration larger than 80 g/L. Therefore, the reuse purposes of spent pickling liquid were specified as the raw materials for hydrochloric acid, sulfuric acid, ferric oxide (powder), ferric chloride, or ferrous sulfate [22,24]. Regarding the recycling or regeneration methods of spent pickling liquid or liquor, they have been reviewed in the literature [33,34]. Various hydrometallurgical options (e.g., pyro-hydrolysis) for the recovery of acid and second by-products (e.g., $FeCl_3$) from spent pickling solutions have been used, depending on waste for disposal, energy input, complexity of equipment installation, required space, and benefit/cost ratio [34]. In Taiwan, the industrial process for recycling spent pickling liquid was based on the vacuum distillation system as depicted in Figure 5. Similar to the spent acid etchant recycling, the by-product ferric chloride ($FeCl_3$) was commonly reused as a coagulant in the wastewater treatment plants.

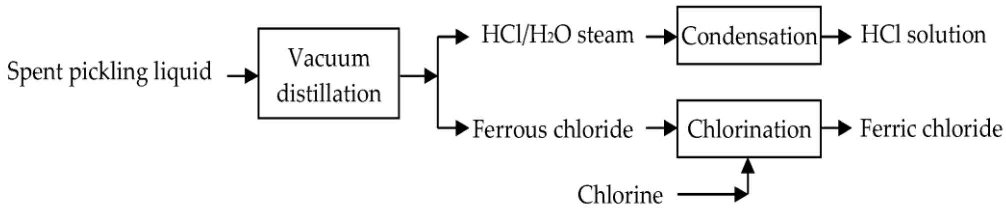

Figure 5. Basic flowchart of spent pickling liquid recycling.

3.4.3. Spent DMF-Contained Liquid

This IHW was mostly derived from the wet coating and curing processes in the polyurethane (PU) synthetic leather industry (one of plastic products manufacturing industries). As mentioned above, this spent liquid containing dimethyl formamide (DMF) of less than 30 wt% must be reused as a raw material for PU synthetic leather, resin, or DMF solvent. Due to the richness in water and DMF, this spent solution was commonly processed by the distillation system for recovering DMF as shown in Figure 6. Because DMF is liable to be hydrolyzed to form formic acid, the recovered DMF will be further refined to remove the hydrolyzed by-product using a vacuum distillation system [20]. It should be noted that the recovery technology for the removal of DMF from the wet type of waste gas may be the absorption method due to its lower energy input [35].

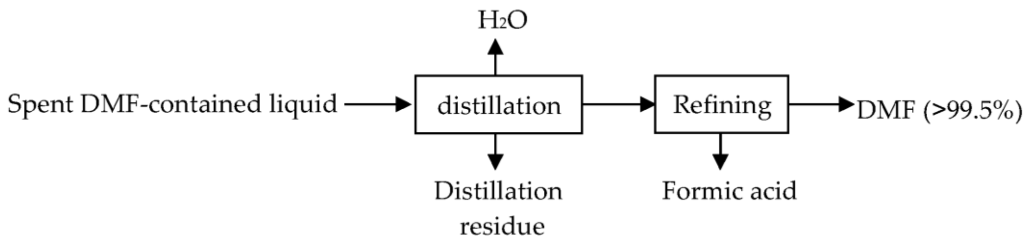

Figure 6. Basic flowchart of spent DMF-contained liquid recycling.

4. Conclusions and Recommendations

With the promotion of IHW recycling (or reuse) in Taiwan under the authorization of the WMA since 2000, the annual reported amounts of IHW generation ranged from 1200 thousand metric tons to 1600 thousand metric tons over the period of 2010–2020, reflecting a balanced relationship between the industrial production and IHW management. More significantly, the amounts of IHW recycling (or reuse) indicated an increasing trend from 684,978 metric tons in 2010 to 952,159 metric tons in 2020, reaching a recycling (or reuse) rate of over 60%. Based on the principles of resource recycling and circular economy, some case studies of specific types of industrial hazardous waste (including spent acid etchant, spent pickling liquid, and spent dimethyl formamide-contained liquid) were addressed to echo the government efforts in sustainable material management by stepping with international trends. In conclusion, this sustainable waste management approach for IHW recycling (or reuse) not only raises green productivity but also reduces the environmental risks from traditional treatment methods such as incineration and landfill.

In this work, we have found an increasing trend in the IHW generation, especially in spent solvents and waste (or sludge) containing heavy metals. To further upgrade the IHW recycling (or reuse) rate in the internal supply chain and circular economy paradigm, the Taiwan government should revise the regulatory terms such as 5R (“reduction”, “reuse”, “recycling”, “recovery”, and “reclamation”), waste/discard/scrap/resource, and renewable resource/by-product. The joint-ministerial efforts by the EPA and the MOEA shall promulgate the specific regulations for high-tech industries (e.g., semiconductor and opto-electronics manufacturing) to conduct a sustainable material management through industrial waste recycling (or reuse) and cleaner production. In addition, several IHW items, including spent solvent and waste (or sludge) containing precious metals, may be listed as the R-type (i.e., R-25) such as spent solvent and waste (or sludge) containing precious metals, which can be recycled to raw materials in the industrial sector. With the prevalence of corporate social responsibility (CSR), the environmental performances of waste management may provide the external incentives in the accounting/cost system of the enterprise or business.

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