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Chemical Waste Management in the U.S. Semiconductor Industry

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Abstract: Sustainability has become the biggest concern of the semiconductor industry because of hundreds of high-purity organic and inorganic compounds involved in manufacturing semiconductors not being treated economically. The aim of this study was to understand how semiconductor companies manage their chemical wastes, by analyzing the U.S. Environmental Protection Agency's Toxics Release Inventory data for hydrogen fluoride, nitric acid, ammonia, *N*-methyl-2-pyrrolidone, hydrochloric acid, nitrate compounds, and sulfuric acid. Cluster analysis was adopted to classify the U.S. semiconductor companies into different performance groups according to their waste management approaches. On the basis of the results, twenty-seven companies were classified in the "best performance" category for the waste management of two or more chemicals. However, 15 companies were classified in the worst performance categories. The semiconductor companies can refer to our results to understand their performance and which companies they should benchmark regarding chemical waste management. City governments can also refer to our results to employ suitable policies to reduce the negative impacts of the chemical waste from regional semiconductor companies.

Keywords: waste management; sustainability; cluster analysis; semiconductor

1. Introduction

The semiconductor industry is one of the largest industries in the world with a production value of approximately US$400 billion [1]. The semiconductor production process usually comprises deposition, resist coating, light exposure, etching, resist removal, and rinsing, which generate considerable acid waste [2]. More than 200 high-purity organic and inorganic compounds and large quantities of ultrapure water are used during the production of semiconductor chips [3]. Furthermore, most of the discharged chemicals, incinerated at high temperatures, are human carcinogens, which could pose a serious health risk if not treated properly. Thus, wastewater from semiconductor fabrication facilities commonly contains a range of harmful contaminants, such as solvents, arsenic, antimony, acids, alkalis, salts, fine oxide particles, and other pure organic and inorganic compounds [4]. Numerous approaches have been developed to treat the pollution arising from different manufacturing processes. Several methods, such as distillation, adsorption, membrane separation, extraction, freeze concentration, photolysis, and melt crystallization, have been explored to recycle or recover organic solvents from a waste photoresist stripper [5,6]. Wastes such as chemical mechanical polishing wastewater can be treated to effectively reduce the suspension of silica particles and completely remove cetyltrimethylammonium bromide [7]. Chemical coagulation and reverse osmosis are used to remove 99% of the suspended oxide particles and reduce the chemical oxygen demand so that the wastewater can be reused post-treatment [8]. In semiconductor manufacturing, hydrofluoric acid is widely used in the etching processes and for cleaning wafers and quartz tubes. According to the Semiconductor Industry Association, waste solutions of hydrofluoric acid account for more than 40% of the hazardous substances produced in the semiconductor industry [9]. Excessive hydrofluoric acid can cause bone disease and tooth spots. Waste solutions of hydrofluoric acid are tightly regulated, and regulatory authorities are required to provide suitable treatment. A variety of methods have been developed and applied to treat hydrofluoric acid wastewater, including chemical coagulation with polyaluminum chlorides or aluminum sulfates, calcium salt precipitation, montmorillonite electrocoagulation, ion exchange, precipitate flotation, and reverse osmosis with montmorillonite or calcite [9].

Because environmental protection and sustainable development have become critical concerns, the semiconductor industry has gradually adopted sustainability considerations. Recently, the Carbon Disclosure Project launched a ban on hazardous substances that are unsustainable and cause global warming. Hence, the semiconductor industry faced various pressures and challenges [7]. Some companies have proactively solved these challenges and mitigated related risks, by reducing their reliance on chemicals and improving the treatment of water before discharge. To treat hazardous waste on-site and maintain strict environmental standards, some semiconductor manufacturers such as Samsung and Intel have invested in green technologies [10]. Other semiconductor companies (e.g., Hadco Corporation, Bindura Nickel Corp, and Cytec Solvay Group) have used different metal recovery techniques, such as electrowinning, to quantitatively remove copper from waste effluents and damage hydrogen peroxide [11–13]. Although many semiconductor companies have attempted to reduce the negative impacts of their chemical waste, few studies have been conducted to analyze their waste management performance. For example, Hsu et al. [7] used the fuzzy Delphi method and analytic network process to construct a sustainability-balanced scorecard for the semiconductor industry. Villard et al. [14] analyzed semiconductor manufacturing enterprises according to seven specific environmental indicators to assess the impact of wafer-manufacturing on environmental standards.

The aim of this study was to investigate the reactions of US semiconductor companies to environmental concerns and their methods of managing chemical waste. According to waste management hierarchy of the US Environmental Protection Agency (EPA), the best approach for managing chemical waste is source reduction and reuse, followed by recycling, recovery, treatment, and disposal [15]. Companies may incorporate different approaches to managing their chemical waste, due to limitations of the manufacturing process. We collected chemicals that were recycled, recovered, treated, and released (disposed) by the semiconductor companies. The chemical wastes investigated in this study included Hydrogen Fluoride (HF), Ammonia (NH_3), Nitric Acid (HNO_3), *N*-methyl-2-pyrrolidone (NMP), Hydrochloric Acid (HCl), Nitrate Compounds (NO_x) and Sulfuric Acid (H_2SO_4). Data were retrieved from the Toxics Release Inventory of the US EPA. Then, we used cluster analysis to classify the companies into groups according to their waste management approaches. The results indicate how each chemical was managed in the semiconductor industry and which companies used the best chemical waste management techniques. These techniques may be referred to by the poorly performing companies. Moreover, we analyzed the relationship between company locations and their chemical waste management performance. This study provides city governments with an overview of the existing semiconductor companies in their city. In addition, we examined the management of chemical waste by semiconductor companies from a regional perspective. Poorly performing cities can adopt the environmental policies of the best performing cities regarding the control of chemical wastes from semiconductor companies.

2. Waste Management of HF, NH_3, HNO_3, NMP, HCl, NOx, and H_2SO_4

The process of semiconductor manufacturing generates a significant amount of wastewater, because a huge quantity of ultrapure water is consumed in the course of the chemical mechanical polishing process [16]. High-purity HF is mainly used as a cleaning gas for removing unnecessary chemical substances that stick to the inside of the chemical vapor deposition furnace during semiconductor production [17]. According to a study from the Semiconductor Industry Association, HF accounts for over 40% of the total hazardous materials produced from this industry [18]. HF is a highly dangerous gas, which can damage the esophagus and stomach and cause lingering chronic lung disease, determined pain, bone loss, and nail bed injuries [19]. NH_3, a toxic gas, is used as a blending division for the calibration gases of emission as well as some specialty semiconductor manufacturing. NH_3 is very toxic to aquatic organisms because over-fertilization leaches into water bodies [20]. Moreover, exposure to high concentrations of ammonia causes irritation of the eyes, nose, and throat, and burning of the skin. In the semiconductor industry, HNO_3 is usually handled as a mixture with hydrofluoric acid, which is frequently used for etching and exposing the critical layer in front-end processing to adjust between the diffusion-limited and rate-limited etching. It is the oxidizing ingredient of many etching mixtures for metals such as silver, copper, aluminum, silicon, germanium, and gold [21]. HNO_3 is an extremely corrosive acid capable of rapidly causing chemical burns and even blindness. If the HNO_3 mist is inhaled, health risks such as the corrosion of the mucous membranes, delayed pulmonary edema, and death may occur [22]. In semiconductor processing, NMP is a very efficient polar solvent for resist removal and cleaning [23]. Currently, there exists no sustainable alternative to NMP with similar critical applications. NMP has a low hazard for ecological receptors and low persistence if released into aquatic or terrestrial environments. However, the risk evaluation report for NMP indicated that reproductive and developmental effects are more important health risks than effects on the hepatic, renal, immune, reproductive-developmental, and central nervous systems [24]. Meanwhile, HCl is the main chemical to produce silicon components in the manufacturing of semiconductors, because it not only engraves silica into a mix with an ammonium fluoride solution by using it in-house with nitric acid, but it also dilutes as a cleaning agent and removes residual oxides as well [25]. However, it causes the corrosion failure of transmission tubing, because the reaction of HCl with moisture eats through stainless tubes in plants manufacturing semiconductors [26]. Moreover, HCl may harm human skin, causing burns, ulcerations, or even scars; when inhaled, it may also cause coughing, hoarseness, inflammation, ulceration of the respiratory tract, chest pain, and even acute health effects such as vomiting, diarrhea or nausea [27]. NO_x derives from the partial or complete neutralization of nitric acid in semiconductor manufacturing [28]. Without proper treatment of this chemical waste, drinking water with high nitrate would interfere with the ability of red blood cells to transport oxygen. In an emergency case, it can lead to respiratory and heart problems, and even death [29]. H_2SO_4 uses huge amounts of resist stripping and wafer cleaning material in semiconductor manufacturing plants. Because the reuse of H_2SO_4 is highly valuable in the semiconductor manufacturing process, many techniques have been proposed to recover and purify the H_2SO_4 waste [30]. It is harmful to the eyes and skin and may cause third-degree burns and blindness upon contact. It can damage the lungs and teeth, or even act as a carcinogenic to humans [31].

Semiconductor manufacturers release (on-site and off-site), treat (on-site and off-site), recover, and recycle their chemical waste, in order to adhere to the criteria specified by the US EPA. The on-site release includes the emission of toxic chemicals into the air and discharge into water, onto land, and into underground injection wells, whereas off-site release includes the disposal of undestroyed chemicals in landfills or water. Another on-site treatment approach is used when the number of toxic chemicals destroyed during on-site waste treatment operations. Biological treatment, incineration, and chemical oxidation are the most common approaches for off-site treatment. Off-site treatment quantity depends on the amount of toxic chemicals that leave the facility boundary for treatment and not the amount that is destroyed at the off-site location. Recovery includes the combustion of toxic chemicals in waste to generate heat or electricity. Recycling is generally the optimal method for chemical waste management and includes the recovery of toxic chemicals from waste for reuse.

3. Methodology

In this study, we collected toxic emissions data for HF, NH_3, HNO_3, NMP, HCl, NO_x, and H_2SO_4 from the US EPA Toxics Release Inventory regarding semiconductor manufacturing (NAICS code 334,413) [32]. The chemical waste management techniques of 68 semiconductor manufacturing companies were analyzed. The collected data included the annual amount of chemical waste released on-site, released off-site, treated on-site, treated off-site, recovered, and recycled by semiconductor companies in the United States in 2013. We calculated the percentage of waste handled with different approaches. Thus, we determined the recycled proportion, the recovered proportion, the proportion treated on-site, the proportion treated off-site, the proportion released on-site, and the proportion released off-site for HF, NH_3, HNO_3, NMP, HCl, NO_x, and H_2SO_4.

To understand how semiconductor companies in the United States have managed their chemical waste, cluster analysis was adopted to classify the companies into three or four performance groups according to their waste management approaches. Cluster analysis was performed to separate several elements into homogeneous groups. In other words, data clustering is the process of placing data items into different groups—clusters—in such a way that items in a particular group are similar to each other and different from those in other groups. The most basic form of clustering uses namely the *K*-means algorithm [33]. In this study, *K*-means clustering was adopted because of its simplicity and general applicability with a widely used algorithm in practice [34]. We first selected *K* initial centroids, where *K* is the user-specified number of clusters desired. In the second step, points were assigned to the updated centroids, and the centroids were updated. Each point was assigned to the closest centroid, and each collection of these points formed a cluster. To assign a point to the closest centroid, we required a proximate measure that quantified the notion of "closest" to the specific data under consideration. The Euclidean distance is often used for data points in a Euclidean space, whereas cosine similarity is more appropriate for documents. The data were analyzed as a percentage and hence did not have a unit and was not standardized. For the objective function, we used the sum of the squared error, which is known as the scattering.

$$SSE = \sum_{i=1}^{K} \sum_{x \in C_i} dist(x, \mu(C_i)) \tag{1}$$

where $\mu(C_i)$ is the centroid of cluster C_i and $dist(x,\mu(C_i))$ is the distance between x and centroid of cluster C_i. Given these assumptions, the centroid that minimizes the *SSE* of the cluster is the mean. Using the notation in Equation (1), the centroid (mean) of the *i*th cluster is defined as follows:

$$c_i = \frac{1}{m_i} \sum_{x \in C_i} x \tag{2}$$

where m_i is the number of objects in the *i*th cluster and m is the number of objects in the data set. In normal practice, the default distance is chosen to be Euclidean distance as

$$d_{euclidean}(x, \mu(C)) = \left[\sum_{i=1}^{d} (x_i - \mu(C)_i) \right]^{\frac{1}{2}} \tag{3}$$

for *d*-dimensional of the data point.

Steps 3 and 4 of the *K*-means algorithm involve minimizing the *SSE*. In Step 3, clusters are formed by assigning points to their nearest centroid. In Step 4, the centroids are recomposed to further minimize the *SSE*. The approaches of *CH* index, *DB* index, and *SH* index are generally adapted to determine the optimal value of *K* [35]. In this study, *CH* index was applied by the following formula:

$$CH = \frac{SSB/(M-1)}{SSW/(N-M)} \tag{4}$$

where SSB is the sum square between cluster variance, SSW is the sum square within cluster variance, N is 68 in this study, and M is a number of clusters [36]. The clustering result of the chemical waste management is displayed according to the mean percentage of each approach. We numbered the clusters with the percentage of the preferred waste management approach. According to the waste management hierarchy established by the Pollution Prevention Act of 1990, the preferred management methods are recycling, followed by burning for energy recovery, treating, and, as a last resort, releasing the waste. Hence, companies classified as Type 1 had high percentages of preferred waste management approaches, and companies classified as Type 4 usually had high percentages of undesirable waste management approaches.

4. Results

4.1. Clustering Analysis

We start with the discussion of clustering results regarding HF, where four types of waste management approaches were clustered. Table 1 lists the average percentage of the HF waste managed by the approaches of on-site released, off-site released, on-site treatment, off-site treatment, recovered, and recycled by each semiconductor manufacturer. The Type 1 category includes companies with the best performance. In their manufacturing processes, more than 65.4% of the chemical waste was recycled, approximately 20% was treated, and approximately 13% was released. Only one company was classified in this category. The Type 2 category includes companies in which an average of 0.3%, 96.8%, and 2.9% of the HF waste was recycled, treated, and released, respectively, during the manufacturing process. Thirty-three of the 37 companies were classified as Type 2, and on-site treatment was the most adopted approach. Only one company was classified as Type 3, and all of its waste was treated off-site. Type 4 companies released all their HF waste on-site without any treatment.

Table 1. Clustering results of the HF waste.

Approach	Type 1	Type 2	Type 3	Type 4
On-site Release	1.6%	2.6%	0%	100%
Off-site Release	11.4%	0.3%	0%	0%
On-site Treated	19.3%	95.9%	0%	0%
Off-site Treated	2.3%	0.9%	100%	0%
Recovery	0%	0%	0%	0%
Recycle	65.4%	0.3%	0%	0%
Number of Companies	1	33	1	2

The NH_3 waste management results are provided in Table 2. The Type 1 category includes companies that had the best management method for NH_3 waste. In these companies, 0.6% of the ammonia waste was recycled, nearly 0.1% was recovered, 62.7% was treated, and 36.6% was released on-site (27.4%) and off-site (9.2%). Five companies treating ammonia waste were classified in this category. In the Type 2 companies, 93% of the ammonia waste was treated, 6.7% was released, and 0.3% was recycled. Of the 21 companies analyzed, 11 were classified in the Type 2 category (52.4% of the observations). These companies used the most efficient method for treating the ammonia waste before disposing of it in the environment. Companies employing suboptimal NH_3 waste management techniques were classified as Type 3, where approximately 45.7% of the ammonia waste was treated on-site, 28% was treated off-site, approximately 26% was released, and only 0.3% was recycled. Five companies were classified in this category.

The clustering results of HNO_3 waste are given in Table 3. Type 1 companies treated 98.9%, recycled approximately 0.1%, and recovered 0.1% of the nitric acid waste. Most companies were classified in the Type 1 category and treated nitric acid waste suitably before discharging it into the environment. Type 2 companies treated 99.3% and released 0.7% of their total HNO_3 waste. One company was classified in this category. Companies using suboptimal HNO_3 waste management techniques were classified as Type 3. In these companies, approximately 90% of total HNO_3 waste was treated, and more than 10% of the waste was released; only one company was classified in this category. The Type 4 category includes companies in which 100% of the HNO_3 waste was released without treatment.

Table 2. Clustering results of the NH_3 waste.

Approach	Type 1	Type 2	Type 3
On-site Release	27.4%	4.5%	12.6%
Off-site Release	9.2%	2.2%	13.4%
On-site Treated	7.7%	85.0%	45.7%
Off-site Treated	55.0%	8.0%	28.0%
Recovery	0.1%	0%	0%
Recycle	0.6%	0.3%	0.3%
Number of Companies	5	11	5

Table 3. Clustering results of the HNO_3 waste.

Approach	Type 1	Type 2	Type 3	Type 4
On-site Release	0.8%	0.7%	10%	0%
Off-site Release	0.1%	0%	0%	100%
On-site Treated	98.1%	56.5%	66.6%	0%
Off-site Treated	0.8%	42.8%	23.4%	00%
Recovery	0.1%	0%	0%	0%
Recycle	0.1%	0%	0%	0%
Number of Companies	32	1	1	1

Table 4 shows the clustering results of waste approaches on NMP. The release category occupied a small proportion of all the clusters, and the release of each cluster was close. Therefore, the degree of discrimination was low and thus ignored. The Type 1 category includes companies that recycled 73.6%, recovered 5.2%, treated less than 13% and released 0.9% of their NMP waste. The Type 2 category includes companies with suboptimal NMP waste management: these companies recovered 80%, recycled less than 5%, treated approximately 10%, and released 5% of their total NMP waste. The Type 3 category includes companies that treated 84%, recovered approximately 8%, and released approximately 8% of the NMP waste. The analysis of 30 companies provided a relatively uniform classification result. Table 4 indicates that all companies treated the chemical wastes released by them during semiconductor manufacturing. Ten companies were classified as Type 1, fifteen companies were classified as Type 2, and four companies were classified as Type 3.

Table 4. Clustering results of the NMP waste.

Approach	Type 1	Type 2	Type 3
On-site Release	9.0%	5.2%	6.9%
Off-site Release	0%	0.2%	1.0%
On-site Treated	10.5%	6.0%	2.5%
Off-site Treated	1.7%	3.3%	81.9%
Recovery	5.2%	81.0%	7.6%
Recycle	73.6%	4.3%	0.0%
Number of Companies	11	15	4

Additionally, we also analyzed the waste management approaches of HCl waste and summarize its clustering results Table 5. One company was classified as Type 1, which treated on-site 74.3%, recycled approximately 4.5%, and released 21.2% of the HCl waste. Type 2 companies recycled 0.5%, treated 96.7% and released 2.7% of their total HCl waste. Most companies were classified in the Type 2 category and treated HCl waste suitably before discharging it into the environment. In type 3 companies, more than 48% of total HCl waste was treated on-site, and approximately 52% of the waste was released; only one company was classified in this category.

Table 5. Clustering results of the HCl waste.

Approach	Type 1	Type 2	Type 3
On-site Release	21.2%	2.7%	51.9%
Off-site Release	0%	0%	0%
On-site Treated	74.3%	95.9%	48.1%
Off-site Treated	0%	0.8%	0%
Recovery	0%	0%	0%
Recycle	4.5%	0.5%	0%
Number of Companies	1	17	1

The NO_x waste management results are provided in Table 6. The Type 1 category includes companies that had the best management method for NO_x waste. In these companies, 74.2% of NO_x waste was recycled, and 25.8% was released. These companies used the most efficient method for recycling the NO_x waste before disposing of it in the environment; 24 companies (80% of the observations) treating NO_x waste was classified in this category. In Type 2 companies, 92.6% of NO_x waste was treated, 20% was on-site released and 7.2% was off-site released. Of the 30 companies analyzed, 2 were classified in the Type 2 category. Companies employing suboptimal NO_x waste management techniques were classified as Type 3, where approximately 25.4% of the NO_x waste was treated on-site and 84.5% was released on-site (74.5%) and off-site (10%); only one NO_x waste management company was classified in this category. The Type 4 category includes companies in which 100% of the NO_x waste was released without treatment.

Table 6. Clustering results of the NO_x waste.

Approach	Type 1	Type 2	Type 3	Type 4
On-site Release	0%	20%	74.5%	0.1%
Off-site Release	25.8%	7.2%	10%	99.9%
On-site Treated	0%	0%	25.4%	0%
Off-site Treated	0%	92.6%	0%	0%
Recovery	0%	0%	0%	0%
Recycle	74.2%	0%	0%	0%
Number of Companies	24	2	1	3

The clustering results of H_2SO_4 waste are given in Table 7. Sixteen companies (88.9% of observations) were classified as Type 1, which treated 98.7% and released 1.3% of the H_2SO_4 waste. Most companies were classified as Type 1, and treated H_2SO_4 waste suitably before discharging it into the environment. Type 2 companies treated 49.9% and released 5.1% of their total H_2SO_4 waste. One company was classified in this category. The Type 3 category includes companies in which approximately 31% of total H_2SO_4 waste was treated, and more than 69% of the waste was released.

Table 7. Clustering results of the H_2SO_4 waste.

Approach	Type 1	Type 2	Type 3
On-site Release	1.3%	50.1%	69.4%
Off-site Release	0%	0%	0%
On-site Treated	98.7%	49.9%	30.6%
Off-site Treated	0%	0%	0%
Recovery	0%	0%	0%
Recycle	0%	0%	0%
Number of Companies	16	1	1

4.2. Clustering Results by City and Company

To understand the clustering results from the perspectives of cities and companies, we summarized each company's waste management performance for HF, NH_3, HNO_3, NMP, HCl, NO_x, and H_2SO_4 in relation to geographical location in Table 8. According to our analysis, San Jose (CA, USA), Phoenix (AZ, USA), Sunnyvale (CA, USA), and Austin (TX, USA) had the highest number of semiconductor companies. Regarding the waste management of HF, only one company, located in El Segundo (CA, USA), was classified in the best performance category (Type 1). Two companies, located in Santa Clara and Milpitas, were classified in the worst performance category (Type 4). For NH_3 waste management, five companies, located in Chandler (AR, USA), San Jose, Woburn, and Austin, were classified in best performance category (Type 1). Moreover, five companies, located in San Jose, Santa Clara, Austin, Sherman (TX, USA), and Vancouver (WA, USA), were classified in the worst performance category (Type 3). For the waste management of HNO_3, 91.4% of the analyzed companies were classified in the best performance category. San Jose had the highest number of semiconductor companies as well as the highest number of companies in top performance categories. The worst performing company (Type 4) is located in Richardson (TX, USA). According to the results of the *N*-methyl-2-pyrrolidone waste treatment, four companies were classified in the worst performance category (Type 3). These companies are located in Phoenix, San Diego (CA, USA), Boise (ID, USA), and Austin. For HCl waste management, one company, located in Austin, were classified in best performance category (Type 1). Meanwhile, one company, located in Chandler—was classified in the worst performance category (Type 3). For the waste management of Nitrate (NO_3) compounds, 80% of the analyzed companies were classified in the best performance category. San Jose had the highest number of semiconductor companies and also the highest number of companies in the top performance categories. The three worst performing companies (Type 4) are located in Foster (CA, USA), Portland (MA, USA) and Youngwood (PA, USA). Based on the results of the H_2SO_4 waste treatment, only one company were classified in the worst performance category (Type 3). This company is located in Santa Clara. Most companies (nearly 90% of analyzed companies) were classified in the best performance category. San Jose had the highest number of companies in the best performing categories.

From the perspective of the company, Table 8 shows that there is one company, namely Samsung Austin Semiconductor, which was classified as the best performer for the management of five chemical wastes (NH_3, HNO_3, HCl, NO_3, and H_2SO_4). Moreover, Fairchild Semiconductor was listed as a suboptimal best performer because it manages well with four types of chemical waste: NH_3, HNO_3, NO_3, and H_2SO_4. Eleven companies were classified as the best performers for the management of three chemical wastes, including Sumco Phoenix Corp., On Semiconductor (Phoenix, AR, USA), Avalog Device Inc. (Wilmington, MA, USA), and Wafertech LLC. (Camas, WA, USA); In this group, Texas has two companies—Texas Instrument Inc. (Sherman, TX, USA), Freescale Semiconductor (Austin, TX, USA)—and California has five: Globalfoundries U.S. Inc. (Santa Clara, CA, USA), Microchip Technology Inc. (San Jose, CA, USA), International Rectifier Corp. (El Segundo, CA, USA), TSI Semiconductors LLC. (Roseville, CA, USA), and Spansion Inc. (Sunnyvale, CA, USA). Apart from this, thirteen companies were grouped in the best performance category for the management of at least two chemical wastes. For example, Sanyo N.A. (Forrest, AR, USA), First Solar (Tempe, AR, USA), Emcore Corp. (Alhambra, CA, USA), Voltage Multipliers Inc. (Visalia, CA, USA), Hewlett-Packard Co. (San Diego, CA, USA), Seh America Inc. (Vancouver, WA, USA), Micron Technology Inc. (Boise, ID, USA), Vishay Intertechnology (Malvern, PA, USA), Sunedison Inc. (El Segundo, CA, USA), and Electronic Devices Inc. (Yonkers, NY, USA) comprised the benchmark group for the management of HNO_3 and NO_x waste. IBM Corp. (Foster, CA, USA) was classified in the best performance category for HNO_3 and H_2SO_4 waste management. Voltage Multipliers Inc. (Visalia, CA, USA) and Philips N.A. (Andover, MA, USA) are two of the best performers for Nitrate (NO_3) compounds and HNO_3 waste management. Diodes Inc. (San Jose, CA, USA) is the best performer for the management of NO_x and H_2SO_4 waste. With only one analyzed chemical waste, there are six companies that always showed their best performance in waste management: Innovative Micro Technology (Goleta, CA, USA), Global Communication Semiconductor LLC. (Torrance, CA, USA), and M/A-Com Inc. (Lowell, MA, USA) outperformed for NMP wastes, whereas Truesense Imaging Inc. (Rochester, NY, USA), Honeywell International Inc. (Morristown, NJ, USA), X-Fab Foundries Ag. (Lubbock, TX, USA) outperformed for H_2SO_4 chemical wastes. On the other hand, five companies were classified in the lagging group for their chemical manufacturing, namely E. I. du Pont de Nemours & Co. (Wilmington, DE, USA), Flipchip International LLC. (Phoenix, AR, USA), Micrel Semiconductor (San Jose, CA, USA), Qualcomm Corp. (San Diego, CA, USA), and Cleanpart U.S (Richardson, TX, USA). Moreover, some companies exhibited both the best and the worst performance for chemical treatment. Atmel Corp (Chandler, AR, USA) used the best methods to treat NH_3 waste but the worst methods to treat HCl waste. Micron Technology Inc. (Boise, ID, USA) was classified in the best performance category for HNO_3 and HCl waste management and the worst performance category for NMP waste management. The waste management performance of Intersil Corp. (Milpitas, CA, USA) was the best for NMP and the worst for HF. Furthermore, Globalfoundries U.S. Inc. (Santa Clara, CA, USA) showed the best performance for HNO_3, NO_x, and H_2SO_4, but a lag performance for NH_3. Freescale Semiconductor (Austin, TX, USA) is the best performer for HNO_3, NO_x and H_2SO_4 waste management and simultaneously the worst performer for NMP waste management. With the best performance for HNO_3 waste management and the worst performance in NO_x waste management, Siltronic Corp. (Portland, MA, USA) was classified in this benchmark. Spansion Inc. (Sunnyvale, CA, USA) was the best for HNO_3, NO_x and H_2SO_4 and the worst for NH_3. Seh America Inc. (Vancouver, WA, USA) was classified in the best performance category for HNO_3 and NO_x waste management, and the worst performance category for NH_3 waste management. In addition, Intel Corp. (Santa Clara, CA, USA) exhibited a strong performance for HNO_3 waste management and a poor performance of waste management for two chemicals such as HF and H_2SO_4.

Table 8. Clustering results of chemical waste approaches by company.

State	City	Company	Chemicals						
			HF	NH_3	HNO_3	NMP	HCl	NO_x	H_2SO_4
AR	Forrest	Sanyo N.A.	2		1			1	
	Tempe	First Solar			1			1	
	Chandler	Atmel Corp.	2	1			3		2
	Phoenix	Sumco Phoenix Corp.	2		1	1	2	1	
		Flipchip International LLC.				3			
		On Semiconductor	2	2	1			1	1
CA	Alhambra	Emcore Corp.			1			1	
	San Jose	Cypress Semiconductor	2	3					
		Diodes Inc.			3	2	2	1	1
		Fairchild Semiconductor Corp.	2	1	1		2	1	1
		Maxim Integrated Products Inc.	2		1	2			
		Micrel Semiconductor	3						
		Microchip Technology Inc.	2	1	1			1	
	Visalia	Voltage Multipliers Inc.			1			1	
	Santa Clara	Globalfoundries U.S. Inc.	2	3	1		2	1	1
		Intel Corp.	4	2	1	2	2		3
	Sunnyvale	Spansion Inc.	2						
		Infinera Corp.				2			
		Alpha & Omega Semiconductor	2				2		
	San Diego	Qualcomm Corp.				3			
		Hewlett-Packard Co.	2		1			1	
	El Segundo	International Rectifier Corp.	1		1		2	2	1
		Sunedison Inc.	2		1		2	1	
	Milpitas	Intersil Corp.	4			1			
		Linear Technology Corp.	2						1
	Roseville	TSI Semiconductors LLC.	2		1			1	1
	Goleta	Innovative Micro Technology				1			
	Torrance	Global Communication Semiconductor LLC.				1			
	San Francisco	Bridgelux		2					
	Foster	IBM Corp.	2	2	1	2	2	4	1

Table 8. *Cont.*

State	City	Company	Chemicals						
			HF	NH_3	HNO_3	NMP	HCl	NO_x	H_2SO_4
CO	Colorado Springs	DPIX LLC.				2			
DE	Wilmington	E. I. du Pont de Nemours & Co.						3	
GE	Norcross	Suniva Inc.	2						
ID	Boise	Micron Technology Inc.	2		1	3		1	
IL	Chicago	The Boeing Co.		2		1			
IO	Iowa	Newport Fab LLC (DBA Towerjazz)	2	2	1				
MA	Andover	Philips N.A.		2	1			1	
	Woburn	Skyworks Solutions Inc.		1		1	2		
	Wilmington	Analog Devices Inc.	2		1	1	2		1
	Portland	Siltronic Corp.			1		2	4	
	Lowell	M/A-Com Inc.				1			
	Waltham	Perkinelmer Inc.				2			
	New Bedford	North East Silicon Technologies Inc.	2		1				
MI	Durham	General Motors LLC.	2						
MN	Yonkers	Polar Semiconductor LLC.	2			2	2		
NC	Greensboro	RF Micro Devices Inc.				1			
	Durham	Cree Inc.	2	2	2	2			
NY	Rochester	Truesense Imaging Inc.							1
	Yonkers	Electronic Devices Inc.	2		1			1	
	New York	Toshiba America Inc.		2					
		L3 Communications Holdings Corp.				2			
NJ	Morristown	Honeywell International Inc.							1
OR	Portland	Siltronic Corp	2						
	Hillsboro	TriQuint Semiconductor				2			
		SolarWorld Ag	2	2	1			2	
PA	Malvern	Vishay Intertechnology	2		1	2		1	
	Youngwood	Powerex Inc.	2		1			4	
	Mendota Heights	Avago Technologies	2			1			
TX	Austin	Samsung Austin Semiconductor		1	1	2	1	1	1
		Freescale Semiconductor	2		1	3	2	1	1
		Spansion Inc.		3	1			1	1
	Richardson	Cleanpart U.S			4				
	Allen	Okmetic Inc.					2		
	Lubbock	X-Fab Foundries Ag.							1
	Sherman	Texas Instruments Inc.		3	1	2	2	1	1
WA	Vancouver	Seh America Inc.	2	3	1		2	1	
	Camas	Wafertech LLC.	2	2	1	1		1	
	Bellevue	Emagin Corp.				2			

4.3. Discussion

To further understand the differences between the best performance cluster and the worst performance cluster, we compared the waste management approaches adopted by the best performing company and the worst performance company for each chemical in Table 9. Regarding the waste of HF, International Rectifier was the best performer in Type 1, having recycled 65.4% of the waste, while Intel was the worst performer, having recycled only 0.6% of the waste. With regard to NH_3, the best performer, Samsung Austin Semiconductor, only released 10.4% of the waste onsite. However, the worst performer, Cypress Semiconductor, released 31% of NH_3 wastes. Regarding HNO_3, Cleanpart U.S was listed as the worst performer, because it released 100% of the waste offsite. On the other hand, Samsung Austin Semiconductor, was classified in Type 1, which recycled 0.3%, recovered 2.9%, treated 93.5% and released 3.3% of total disposal waste. With regard to NMP, Avago Technologies recycled 97% of chemical wastes, while Flipchip treated nearly 82% of NMP waste offsite. For HCl, Samsung Austin Semiconductor was the best Type 1 performer, with more than 74% of waste using treatment approach. However, Atmel Corp, the worst performer, treated 48.1% onsite and released 51.9% of waste onsite. First Solar, a Type 1 company regarding NO_x, treated 100% of NO_x offsite. Siltronic Corp was a Type 4 company, having released 100% of the NO_x. In terms of H_2SO_4, Truesense Imaging Inc.

was the best performer, with 100% of the waste treated onsite. Intel was the worst performer which treated 30.6% of the wastes onsite and released 69.4% of the waste onsite.

Table 9. Comparisons between the best performance company and the worst performance company by chemical waste.

Chemical Waste	Approach / Company	Onsite Release	Offsite Release	Onsite Treated	Offsite Treated	Recovery	Recycle
HF	International Rectifier Corp.	1.60%	11.40%	19.30%	2.30%	0.00%	65.40%
	Intel Corp.	0.60%	0.00%	99.40%	0.00%	0.00%	0.00%
NH_3	Samsung Austin Semiconductor	10.40%	32.40%	5.30%	48.30%	0.40%	3.30%
	Cypress Semiconductor	31.00%	0.00%	30.30%	38.70%	0.00%	0.00%
HNO_3	Samsung Austin Semiconductor	0.60%	2.70%	93.50%	0.00%	2.90%	0.30%
	Cleanpart U.S	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
NMP	Avago Technologies	2.00%	0.00%	0.00%	0.00%	1.00%	97.00%
	Flipchip International LLC.	18.20%	0.00%	0.00%	81.80%	0.00%	0.00%
HCl	Samsung Austin Semiconductor	21.20%	0.00%	74.30%	0.00%	0.00%	4.50%
	Atmel Corp.	51.90%	0.00%	48.10%	0.00%	0.00%	0.00%
NO_x	First Solar.	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
	Siltronic Corp.	99.70%	0.30%	0.00%	0.00%	0.00%	0.00%
H_2SO_4	Truesense Imaging Inc.	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
	Intel Corp.	69.40%	0.00%	30.60%	0.00%	0.00%	0.00%

According to the clustering result for HF waste management, most companies were classified in the second-best performance group, in which 96% of the chemical waste was treated on-site. Two companies, located in Santa Clara and Milpitas (CA, USA) were classified in the worst performance category: they released 100% of their chemical waste directly into the environment without any treatment. Although the Santa Clara government created the Office of Sustainability in April 2010 and committed itself to maintaining ecological integrity, our results indicate that improvements are still required. According to the results for the waste management of NH_3, most companies were classified as Type 2 and recycled approximately 75% of their ammonia waste. Two companies classified in the worst performance category for ammonia waste management are located in Texas. Regarding HNO_3 waste, most companies were classified in the best performance category, because they treated nearly 98% of their waste on-site and released only 0.8% without treatment. Only one company, located in Richardson (TX, USA), exhibited a poor performance and did not treat the nitric acid waste after manufacturing. Texas has a strict environmental policy through laws and regulations passed at all governmental levels. It spent US$356.6 million on its environmental and natural resources departments in the fiscal year 2015 [37]. However, our results indicate that the Texas government may need to provide stricter controls on nitric acid waste for semiconductor manufacturing. The results of the waste treatment of NMP indicated that most companies used a combined approach of onsite and offsite treatment. The onsite and offsite release approaches were also popular among the semiconductor companies, because NMP usually does not present a significant risk to the environment [38]. As for the clustering result for HCl waste management, most companies were classified in the second-best performance group, in which 96.7% of the chemical waste was treated on-site (95.9%) and off-site (0.8%). One company, located in Austin (TX, USA) was the best performer, with more than 74% of total chemical waste treated before discharging into the environment. One company, located in Chandler (AR, USA), was classified in the worst performance category: they released 51.9% of their chemical waste directly into the environment without any treatment. In the past, Arizona seemed to not put too much of effort on sustainability [39]. In 2015, Arizona spent $208.2 million in its Environmental Quality and Game and Fish departments [40]. Our results indicate that waste control policies of HCl should be monitored in this area. In addition, the results of the waste treatment of NO_x indicated that 24 companies (80% of analyzed companies) were classified into the best performing group, using recycling approaches for 74.2% of total wastes and off-site releasing for 25.8% of total nitrate compounds wastes. There are three companies listed in the worst-performance category located in Foster (CA, USA), Portland (MA, USA) and Youngwood (PA, USA). Although MA and PA have their own policy to protect the environment and allocated US$1.4 billion and US$7.1 billion respectively in fiscal 2015 [41], there is still room for improvement when it comes to the waste management policy on NO_x. Based on results for the waste management of H_2SO_4, 88.9% of analyzed companies were classified as Type 1 and treated approximately 99% of their H_2SO_4 waste. One company classified in the worst performance category for H_2SO_4 waste management; it is located in Santa Clara, CA, USA.

5. Conclusions

In the semiconductor industry, environmental sustainability during the research, development, and manufacturing of products is crucial. Companies have attempted different approaches to treat their chemical wastes and are searching for efficient waste management approaches to reduce energy costs. In this research, a benchmarking method is proposed to evaluate the chemical waste management performance of semiconductor manufacturers. To the best of our knowledge, this study is the first to address waste management from the perspective of waste management approaches in relation to company locations. Cluster analysis was adopted in this study to classify the U.S. semiconductor companies into different performance groups according to their waste management approaches. The results indicate how each chemical was managed and which companies used the best chemical waste management techniques, which may be referred to by the poorly performing manufacturers. In addition, our results indicate that two companies were classified in the best performance category for the waste management of four or more chemicals. Eleven companies were listed as the best performers for the management of three chemical wastes. Thirteen companies were grouped in best performance category for the management of at least two chemical wastes. With only one analyzed chemical waste, there were six companies that always showed their best performance in waste management, while five companies were classified in the lagging group for their chemical manufacturing. Moreover, eleven companies exhibited both the best and worst performance for chemical treatment, depending on the particular chemical. One company was classified in the worst performance categories for at least two chemical wastes. Semiconductor companies can refer to our results to determine their performance and which companies they should benchmark regarding chemical waste management. City governments can also refer to our results to employ suitable policies to reduce the negative impacts of the chemical waste from regional semiconductor companies.

This research still has some limitations to overcome. For example, the methodology presented here is suitable and useful only for those countries that have a Pollutant Release and Transfer Register (PRTR) disclosure system in place, such as the Toxics Release Inventory in the USA. The waste management results from different countries with the PRTR system can be compared to understand the current global situation. Future research can analyze the management of other chemical wastes. Moreover, other performance evaluation methods, such as data envelopment analysis, can be used to determine the efficiency of waste management approaches.

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