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Comparative Life Cycle Assessment of Nano-Metal Embedded Water Treatment Resins

Mac Gifford

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Mac Gifford

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EXECUTIVE SUMMARY

In an effort to provide drinking water treatment options that are simple to operate, two hybrid resins have been developed that can treat multiple pollutants in a single step. A parent weak base anion exchange resin is embedded with nanoparticles made of either iron hydroxide or titanium dioxide (Fe-WBAX and Ti-WBAX, respectively). These provide targeted treatment for both arsenic and hexavalent chromium, common groundwater pollutants of recent regulatory significance. The project goal is to evaluate the environmentally preferable choice between Fe-WBAX and Ti-WBAX resin for simultaneous treatment of arsenic and hexavalent chromium in drinking water. The secondary goal is to identify where in the product life cycle is the most opportunity to reduce the environmental impact of the use of either product.

Attributional life cycle assessment following the synthesis, use, and disposal of the hybrid resins is conducted to make this comparison. Results are normalized to the mass of resin required to treat a defined volume of water to an acceptable contaminant level, thus capturing the effect of different treatment capacity. The life cycle inventory is compiled including parent weak base anion exchange resin, metal precursors, precipitation chemicals, electricity for oven heating and packed bed pumping, and landfilling. Emission factors from EcoInvent v2.2 are used to convert these inventory items to midpoint environmental and human health impacts.

Fe-WBAX is found to have higher impacts for eutrophication potential, global warming, ozone depletion, and carcinogenics. The synthesis phase contributes 50% - 99% of the total impacts for each impact category. The Ti-WBAX resin is found to have higher impacts for acidification, ecotoxicity, and respiratory effects. The synthesis phase contributes 75% - 99% of the total impacts for each impact category. For either resin, much of the synthesis impacts are from the production of the polymeric parent anion exchange resin which uses many organic chemicals. The next highest impacts are those associated with causing the nanoparticle precipitation; chemicals in the case of Fe-WBAX and oven heating in the case of Ti-WBAX.

Environmental impacts associated with the Ti-WBAX can be most mitigated by effective use of oven heating during synthesis. Manufacturers should verify utilization of full oven capacity and energy efficient ovens. Impacts associated with the Fe-WBAX can be reduced by maximizing pollutant removal capacity through use of post treatment chemicals that can reduce the mass of anion exchange resin needed. It can be learned from this study that benefits of treating drinking water do involve other environmental and human health tradeoffs.

1. INTRODUCTION

Very small drinking water systems serve between 25 and 500 people and are often in rural locations. An estimated 84% of water utilities in the United States fall into this category and account for 79% of all maximum contaminant level (MCL) violations (United States Environmental Protection Agency, 2007). These systems face unique challenges due to their size, such as lack of operational expertise and economies of scale working against them, but serve people who are still equally entitled to a clean water supply.

Two prevalent groundwater pollutants that are challenging for small systems to remove are hexavalent chromium and arsenic. Hexavalent chromium (Cr) is an oxidized metal for which California recently enacted an enforceable MCL of 10 parts per billion (ppb). One of the leading treatment technologies is anion exchange (Brandhuber, et al., 2004). The MCL for arsenic (As) was lowered to 10 ppb in 2006 due to a variety of human ailments including cancer of the bladder, lungs, and skin. Treatment processes including adsorption to iron have been extensively studied (Speital, et al., 2010) but many small systems still struggle to comply. For example, the Tohono O'odham Utility Authority (TOUA) which oversees many small systems in Arizona reports 36% of service locations average 10 to 32 ppb of As (Tohono O'Odham Utility Authority, 2010).

In an effort to provide treatment options that are simple to operate, two hybrid resins have been developed that can remove multiple drinking water contaminants in a single step. Nanoparticles made of either iron (Fe) hydroxide or titanium (Ti) dioxide are precipitated using heat or chemical energy on the inside of a parent weak base anion exchange resin (WBAX). The resulting product provides targeted treatment for both Cr on the WBAX and for As on the metal nanoparticles. These non-soluble angular beads are approximately 1 millimeter in diameter. They can be packed in a small cartridge for individual household use, or a larger vessel to treat water as it is pumped out of a well. Previous studies have established synthesis protocols for the nano-iron embedded or nano-titanium embedded weak base anion exchange resins (Fe-WBAX and Ti-WBAX, respectively) and have explored their treatment efficacy (Gifford, Westerhoff, & Hristovski, 2014). However the environmental impacts of their use have not been quantified, and it is not clear if either of the two resins is superior in terms of environmental performance.

1.1 Goal

The project goal is to conduct a Life Cycle Assessment to answer two questions. What is the environmentally preferable choice between Fe-WBAX and Ti-WBAX resin for simultaneous treatment of arsenic and hexavalent chromium in drinking water? Where in the product life cycle is the most opportunity to reduce the environmental impact of the use of either product?

2. METHODOLOGY

The environmental impacts of two metal oxide-weak base anion exchange resins are to be assessed via comparative, attributional life cycle assessment (LCA). This is to be accomplished in three phases, which are described in detail in the following sections. First a functional unit must be defined to compare with. Next, the system boundary will be defined, which will enable the life cycle inventory to be compiled. This inventory is a list of all material and energy inputs into and out of the system boundary. The quantities of these inputs will be scaled according to the functional unit. Finally, the environmental impacts associated with the line items from the inventory are assessed. This will be done by using impact factors. This approach will enable comparison of the two resins from an environmental standpoint, as well as identification of what phase of the resin life cycle has the largest potential for environmental improvement.

2.1 Functional Unit

The proposed functional unit is 20 million gallons (MG) of drinking water treated to a minimum acceptable level. Twenty MG represents the annual average domestic water use of 500 people. A minimum level of use characteristics such as fines lost, chemical stability, and resin durability are assumed to be met by either resin.

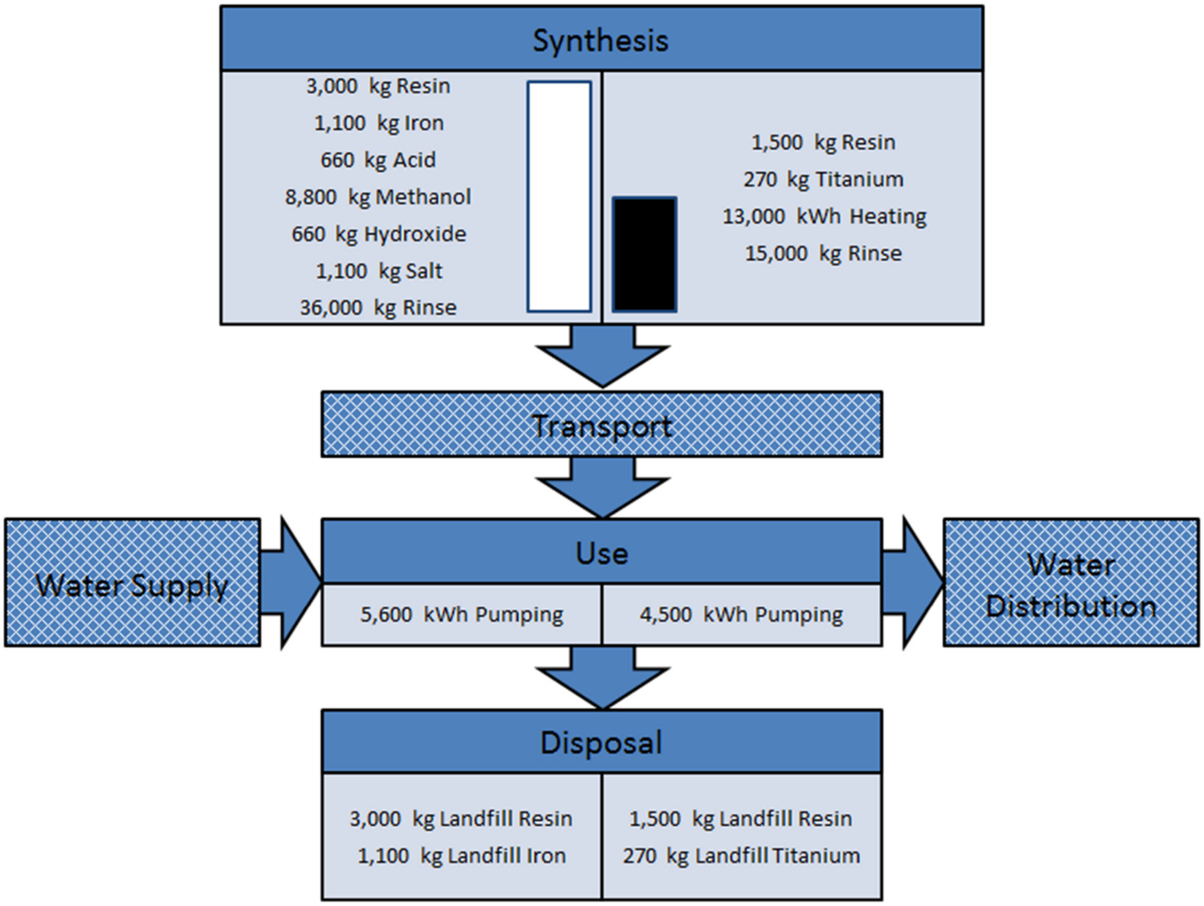
In order to fairly compare disparate pollutant removal capacities between the two resins it is requisite to define a raw water quality and treated water quality goal. This study assumes a raw water quality of 20 ppb Cr and 20 ppb As. These levels are sufficiently high that treatment would be required beyond blending with uncontaminated wells. The assumed water treatment quality goal is 8 ppb Cr and 8 ppb As, which provides a margin of safety beyond the federal mandated 10 ppb As maximum and California state mandated 10 ppb Cr maximum. It is therefore equivalent to think of the functional unit as a mass of resin required to remove 12 ppb As and 12 ppb Cr from 20 MG of water. The mass of hybrid resin included in this LCI is therefore the mass required to treat a volume of water defined by the project functional unit keeping both pollutants below the defined limit. A low capacity to remove either pollutant would result in an increased mass of resin considered.

The mass of each resin required will depend on the capacity to remove each pollutant, which was previously determined (Gifford, Westerhoff, & Hristovski, 2014). The Fe-WBAX has a Cr removal capacity of 300 μg/g and an As removal capacity of 500 μg/g at the concentrations of interest. Therefore treating the functional unit worth of water would require 3,000 kg if determined by Cr capacity or 1,800 kg if determined by As capacity. The larger is selected since it would be unacceptable to keep using the resin after Cr capacity was exhausted even if it was still removing As. The Ti-WBAX resin has a Cr removal capacity of 630 μg/g and an As removal capacity of 600 μg/g at the concentration of interest. It is therefore limited by its As capcity, and requires 1,500 kg of resin to treat the functional unit worth of water.

2.2 System Boundary

This LCA is unique because it follows the life cycle of the treatment product itself instead of the water. The system boundary to be evaluated for these two resins has three principle phases: Synthesis, Use, and Disposal. Figure 1 depicts this boundary. Data sources and details for each phase are then described.

Figure 1



2.2.1 Synthesis The methods for synthesis of the hybrid resins have been previously described (Elton, Hristovski, & Westerhoff, 2013; Hristovski, et al., 2008) and proposed modifications have been quantified (Gifford, Westerhoff, & Hristovski, 2014). They each require inputs of the parent ion exchange resin, a precursor solution consisting of a high concentration of aqueous metal, and some post treatment chemicals. Differences between them reside in the method of metal precipitation. The Fe-WBAX uses chemical precipitation including methanol and sodium hydroxide. The Ti-WBAX uses heat-induced hydrolysis, expending electricity.

The amount of electricity required to heat the Ti-WBAX at 80°C was estimated by two methods and the more conservative method used. First, the physical heat transfer relationship was used

$$E=MCdT/e$$

where E is energy in kWh, M is the mass of air heated in kg, C is the air heat capacity in kJ/kgK, dT is the change in temperature, and e is the oven efficiency. Assuming a 1 cubic meter size oven which contains 1.205 kg of air, heat capacity of 1.005 kJ/kgK, a heat change from 20°C, and a 30% efficiency, the oven would require 0.07kWh. This is compared to empirical observations by appliance vendors on the energy use of an oven (Saving Electricity, 2013) showing that heating 2 cubic meters to 175°C uses 2 kWh. This study interpolates to use half that oven size and 40% of that temperature to estimate an oven electricity usage of 0.4 kWh. As this is larger than the physically estimated usage, 0.4 kWh will be assumed.

2.2.2 Use The principle inventory of the use phase is the energy required to pump water through the resin. Pumping energy is often identified as the largest environmental life cycle impact associated with water supply (Stokes & Horvath, 2011) and is therefore included in this inventory. The required energy to pump water through the resin bed will be computed from the reported headloss per bed depth reported from the parent resin specification sheets. This assumes the headloss through either hybrid resin is the same as the parent resin, which is reasonable since the embedded nanoparticles do not add exterior surface friction. The main source of difference for energy required by the two hybrid resins will stem from different masses of resin required, as higher mass of resin requires more energy to pump through. Energy for pumping from the source or after treatment are not considered.

The bulk weight of moist resin is 1.1 kg per liter (Swiss Center for Life Cycle Inventories, 2010), allowing to convert the required mass of resin calculated in Section 2.1 to a volume of required resin. An aspect ratio of the cylindrical vessel containing the resin is assumed to be 3. It is more reasonable to assume a constant aspect ratio than diameter since if a larger volume of resin was used a larger diameter vessel would be used also, avoiding an overly tall vessel. The Fe-WBAX vessel is therefore estimated to be 3.5 feet in diameter and 10 feet tall. The Ti-WBAX vessel is estimated as 3 feet in diameter and 8 feet tall.

Pump power can be estimated knowing the vessel dimensions according to the equation

$$P=QpgH/n$$

where P is pump power in kW, Q is water flow rate in gallons per minute, p is water density in pounds per cubic foot, g is acceleration due to gravity in feet per square second, H is headloss through the resin in feet, and n is pump efficiency. The flow rate defined in Section 2.1 is 20 MG per year, equivalent to 38 gallons per minute. Water density is 62.4 pounds per cubic foot and acceleration due to gravity is 32.2 feet per square second. Headloss in the resin bed at a loading rate of 10 gpm/square foot is 2.25 psi per foot of bed depth (Rohm and Haas, 2008), equivalent to 5.19 feet of head per foot of bed depth. Pump efficiency is assumed to be 60%. Using the separate bed depths of the two resins yields required pump power for Fe-WBAX as 0.64kW and 0.51 kW for Ti-WBAX. These are equivalent to 5,600 kWh and 4,500 kWh over the course of one year, respectively.

2.2.3 Disposal Owing to low regeneration efficiency and for ease of operation on behalf of the small systems, the embedded resins are assumed to be single use. As soon as the bed exceeds the allowable level for either pollutant, it is considered exhausted and must be replaced. The spent resin, comprised of the WBAX resin and the metal, is landfilled. This study assumes disposal to a normal landfill, and future work will determine if the potential hazardous waste classification may require special landfill accommodations which cause alternate environmental impacts.

2.2.4 Exclusions The system boundary excludes a few notable items from the life cycle inventory. The inventory will not include materials of the treatment plant itself such as piping, valves, and contactor vessels. These materials are required for physical operation of the water treatment technology, but they are only loosely attributable to the resin itself.

Transportation of the resin has also been excluded, including moving the parent resin to the lab, transporting the hybrid resin to the water treatment site, and haul of the exhausted resin away from the site. While the impacts associated with this travel are likely substantial, they would vary widely based on an arbitrary selection for treatment location.

Since this study follows the impacts associated with the hybrid resin, those associated with the water are excluded. Items such as well pumping, source water depletion, and distribution pumping are excluded. These would be the same for either resin anyway.

2.3 Environmental Impacts

Environmental impacts will be estimated by multiplying the life cycle inventory items with their respective impact factors. Impact factors will be obtained from the EcoInvent database version 2.2 (Swiss Center for Life Cycle Inventories, 2010). These impact factors estimate the total environmental impacts that a single inventory item has normalized to a unit, typically mass, in terms of equivalent risk. It is important to match each inventory line item identified in the system boundary to a representative impact factor. Some of these matches are described below.

An impact factor for a general anion exchange resin is available (Anion Exchange Resin – Synthesis). It represents a strong base anion exchange resin made of polystyrene, functionalized with chloromethyl methyl ether and trimethylamine, and 50% moisture content. The Fe-WBAX and Ti-WBAX resins being studied use a weak base anion exchange resin made of phenol-formaldehyde polycondensate, has undergone an unknown functionalization, and a 60% moisture content (Rohm and Haas, 2008). Though not a perfect representation this is deemed an appropriate match for an impact factor since they are both organic polymer bases with some form of functionalization and high moisture content.

Many chemical inventory items correlated closely with impact factors. Sulfuric acid, ferric chloride, sodium hydroxide, methanol, and sodium chloride each had impact factors with matching CAS numbers and descriptions. The titanium oxysulfate precursor was matched with the impact factor for titanium dioxide via sulfate production process. Electricity impact factors were selected as a supply mix, medium voltage, at grid, with average United States production data.

The impact assessment categories to be evaluated are defined by TRACI (Bare, 2002). This system is of interest as it was developed in the United States and covers a range of environmental and human health midpoint impacts. Some of the impact categories to be assessed include non-cancer toxicity, acidification, and global warming potential. Toxicity is of interest due to chemicals used in synthesis such as methanol and disposal of possible radioactive wastes. This generated toxicity may be compared to the toxicity avoided by removing the drinking water pollutants. Acidification is of interest due to acids used in synthesis. Global warming potential is likely due to petroleum in the parent resins and column pumping energy.

3. RESULTS AND DISCUSSION

3.1 Life Cycle Inventory

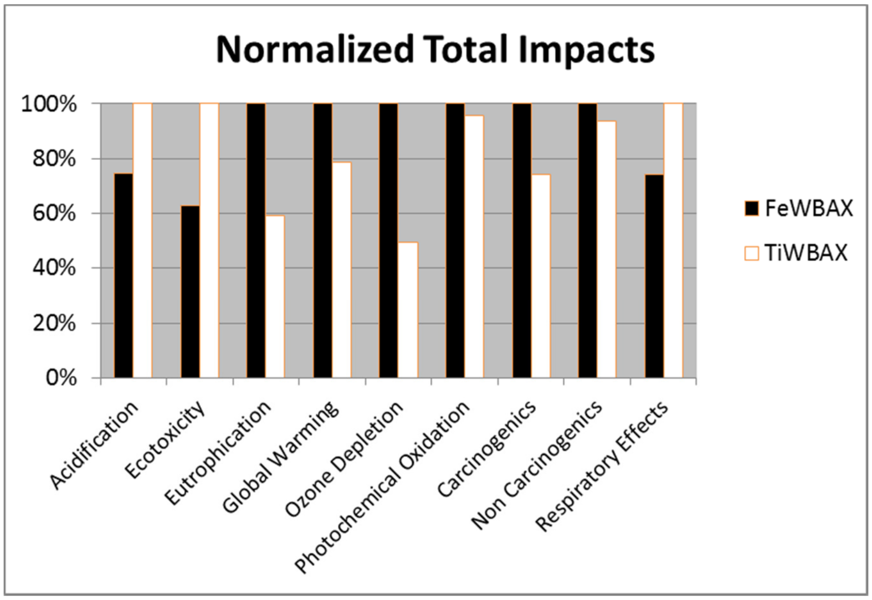
The life cycle inventory was first compiled for each resin, and scaled to the mass of resin required to treat the functional unit (20 million gallons treated water). Items included in this inventory are summarized in Figure 1. The iron based resin (Fe-WBAX) has a limiting pollutant capacity of 300 micrograms chromium removed per gram resin, requiring 3,000 kg of resin to treat the functional unit. The synthesis phase of this resin includes high chemical usage. The energy required during use phase equals the headloss through a packed bed of the required mass of resin. Estimated base on pump head relationships, this totals 54 feet of headloss requiring 5600 kWh to overcome over the course of one year of pumping to deliver the functional unit. Disposal after single use is to a landfill.

The titanium based resin (Ti-WBAX) has a limiting pollutant capacity of 600 micrograms arsenic per gram resin, requiring 1,500 kg of resin to treat the functional unit. The synthesis phase of the resin requires energy to heat an oven for hydrolysis. Heat required for a one cubic meter oven to reach 80°C for 1 hour is estimated as 0.4 kW, resulting in 13,000 kWh demand for a scaled-size oven to heat for 24 hours. Pumping during use phase must overcome 43 feet of headloss, requiring 4500 kWh of pump energy. Disposal after single use is to a landfill.

3.2 Life Cycle Impact Assessment

TRACI midpoint environmental impacts associated with all life cycle inventory items are estimated by use of impact factors obtained from EcoInvent v2.2 (Swiss Center for Life Cycle Inventories, 2010). The total impacts of all life cycle phases for each resin in each impact category is shown in Figure 2. These impacts are normalized to eachother to serve as a comparison between the two resins.

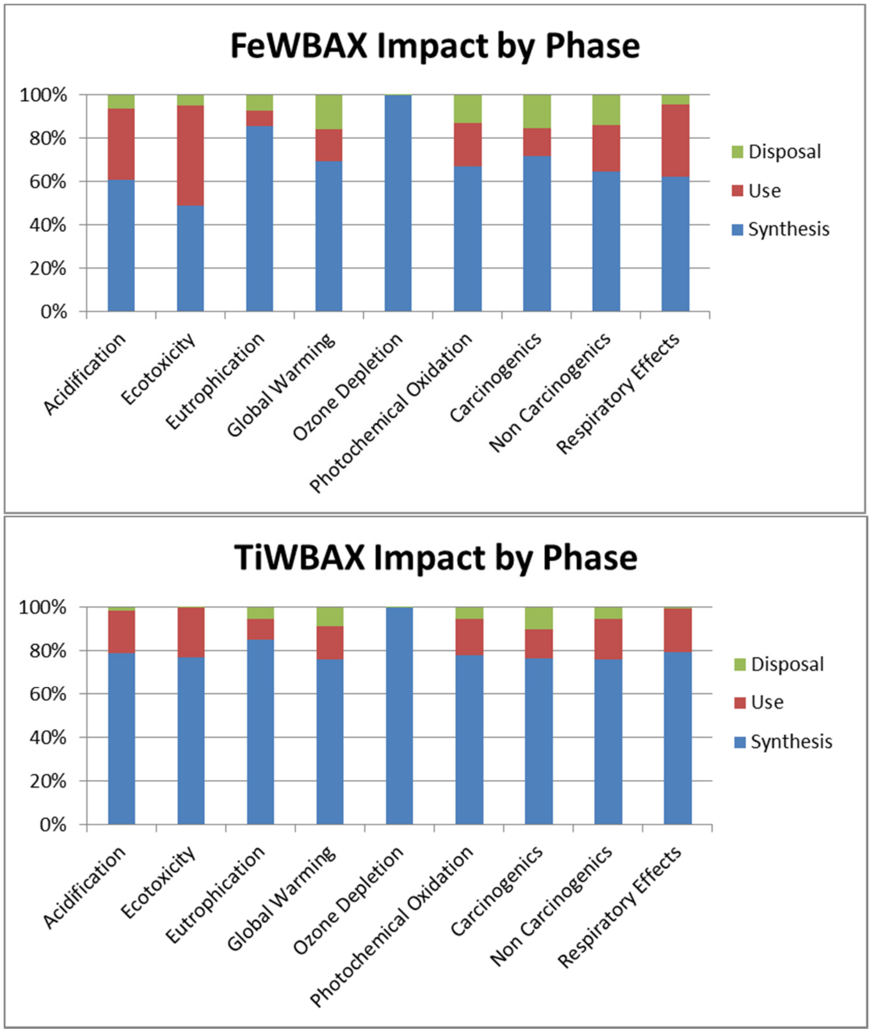
Figure 2



Fe-WBAX is found to have higher impacts for eutrophication potential, global warming, ozone depletion, and carcinogenics. The Ti-WBAX is found to have higher impacts for acidification, ecotoxicity, and respiratory effects. They are very similar for photochemical oxidation and non-carcinogenic toxicity. The largest difference between them is in ozone depletion, where the Fe-WBAX impact is twice as high as Ti-WBAX. In the other differentiated categories variances range from 20% - 40%.

In order to understand the source of these variances the results were next analyzed by phase. The impacts of each resin broken up by contribution from each phase is shown in Figure 3 for each resin. For the Fe-WBAX resin the synthesis phase contributes 50% - 100% of the total impacts for each impact category. The use phase contributes 0% - 50% to each category, and the disposal phase contributes 0% - 15%. For the Ti-WBAX resin the synthesis phase contributes 75% - 100% of the total impacts for each impact category. The use phase contributes 0% - 20%, and the disposal phase contributes 0% - 10% for each category.

Figure 3



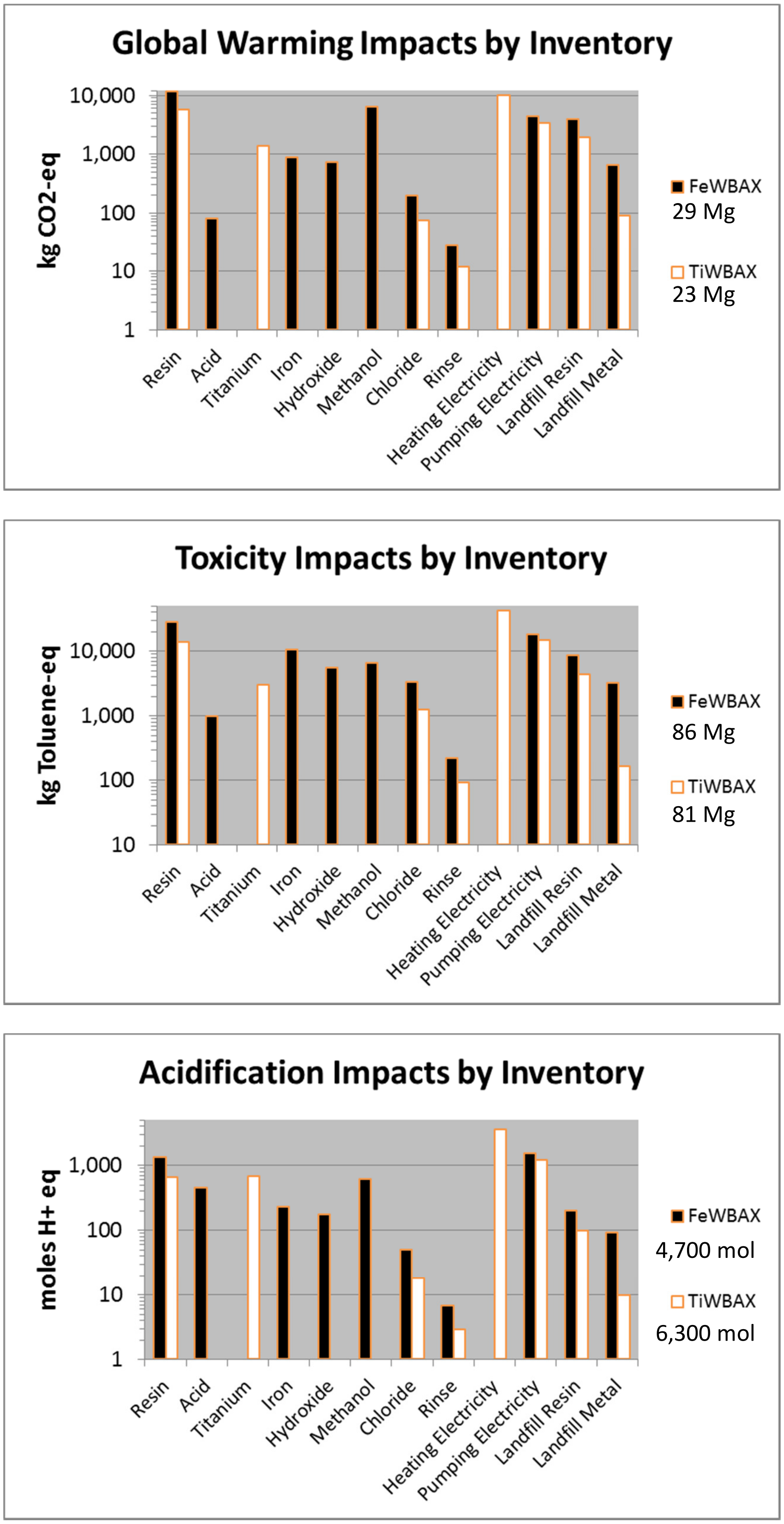
It is very evident that the synthesis phase dominates all life cycle phases for both resins. This is most evident in the case of ozone depletion, where over 99% of the calculated impact for either resin happens during synthesis. This is due almost exclusively to the production of the parent anion exchange resin, which has an emission factor four orders of magnitude higher than that associated with any other inventory item. Further research into the production method for polystyrene anion exchange resin reveals usage of many organic chemicals, including divinylbenzene, chloromethylesther, petroleum ether, dimethylamine, and benzene (Kunin, 1958). These chemicals are the likely reason impacts from use of anion exchange resin are so high since they have high carbon footprints, and human or environmental toxicity.

The other synthesis impacts associated with the Fe-WBAX resin synthesis are primarily from the cumulative impact of the chemicals used to precipitate the iron hydroxide nanoparticles. The synthesis impacts associated with the Ti-WBAX stems primarily from the energy required to heat the resin in an oven to hydrolyze the titanium dioxide nanoparticles. These impacts are very sensitive to assumptions made about the oven utilization, including the amount of resin heated per volume of oven. This is also an area where environmental performance can be improved if it can be shown that shorter heating times are acceptable. Oven utilization efficiency is likely to increase in the future as adoption of these resins increases and production scales since the manufacturers can reduce electricity costs by filling the ovens to capacity.

Impacts associated with the use phase of the Fe-WBAX are approximately 25% larger than those associated with the use phase of the Ti-WBAX. This is due to the larger mass of resin required and subsequent higher headloss that must be overcome by pumping. Packed bed columns were assumed to maintain a 1:3 width to height aspect ratio. This means that even though two times as much volume of Fe-WBAX resin is required to treat an equivalent volume of water as the Ti-WBAX resin, the bed depth only increased by 25% with the rest of the volume compensated by increased column diameter. Different assumptions about bed configuration would alter the results, but the total impacts would still be relatively small compared to synthesis impacts.

Further understanding of the impacts associated with the synthesis phase for each resin is next explored. Figure 4 compares the impacts for three midpoint indicators (global warming potential, ocean acidification potential, and human non-carcinogenic toxicity) delineated by each inventory item. Please note the log scale.

Figure 4


Global Warming Impacts by Inventory
kg CO2-eq
10,000
1,000
100
10
1
Resin
Acid
Titanium
Iron
Hydroxide
Methanol
Chloride
Rinse
Heating Electricity
Pumping Electricity
Landfill Resin
Landfill Metal
■ FeWBAX
29 Mg
□ TiWBAX
23 Mg
Toxicity Impacts by Inventory
kg Toluene-eq
10,000
1,000
100
10
Resin
Acid
Titanium
Iron
Hydroxide
Methanol
Chloride
Rinse
Heating Electricity
Pumping Electricity
Landfill Resin
Landfill Metal
■ FeWBAX
86 Mg
□ TiWBAX
81 Mg
Acidification Impacts by Inventory
moles H+ eq
1,000
100
10
1
Resin
Acid
Titanium
Iron
Hydroxide
Methanol
Chloride
Rinse
Heating Electricity
Pumping Electricity
Landfill Resin
Landfill Metal
■ FeWBAX
4,700 mol
□ TiWBAX
6,300 mol

The Fe-WBAX is found to have a total of 20,000 kg of CO2-eq in the synthesis phase and 29,000 kg of CO2-eq overall, compared to 17,000 CO2-eq synthesis and 23,000 kg of CO2-eq overall for Ti-WBAX. The Fe-WBAX has a higher impact from the parent anion exchange resin due to higher mass of resin required to treat an equivalent volume of water. The next highest impact is from methanol, which is an organic solvent and has high carbon footprint. The Ti-WBAX uses less parent anion exchange resin but still has significant impact associated with it. It also uses less titanium precursor than the Fe-WBAX uses iron precursor, but the carbon footprint is still higher. The primary synthesis impact associated with the Ti-WBAX is the electricity required for oven heating. The overall synthesis impact is smaller due to higher capacity for pollutant removal and not using methanol or other chemicals.

The acidification potential and human toxicity impacts associated with each resin broken down by inventory item show similar overall trends as the global warming potential. The largest impacts are from the heating and pumping electricity and the parent anion exchange resin.

In an effort to simplify future use of the results of this LCA, impact factors associated with the Fe-WBAX and Ti-WBAX are presented in Table 1. These were found by summing the total impacts by phase and normalizing to 1 kg of resin (instead of to one functional unit). For consistency with data observed in the EcoInvent database, the synthesis and disposal phases are presented separately with the use phase omitted.

Table 1

	Acidification (moles H+ Eq)	Ecotoxicity (kg 2,4-D Eq)	Eutrophication (kg N)	Global Warming (kg CO2 Eq)	Ozone Depletion (kg CFC-11 Eq)	Photo chemical Oxidation (kg Nox Eq)	Carcinogenic (kg Benzene Eq)	Non Carcinogenic (kg Toluene Eq)	Respiratory Effects (kg PM2.5 Eq)
Fe-WBAX Synthesis	9.38E-01	1.04E+00	2.16E-03	6.57E+00	1.73E-04	9.10E-03	1.28E-02	1.82E+01	3.79E-03
Fe-WBAX Disposal	9.58E-02	1.07E-01	1.82E-04	1.50E+00	1.09E-08	1.75E-03	2.76E-03	3.94E+00	2.61E-04
Ti-WBAX Synthesis	3.28E+00	5.26E+00	2.57E-03	1.15E+01	1.72E-04	2.04E-02	2.03E-02	4.07E+01	1.32E-02
Ti-WBAX Disposal	7.25E-02	2.69E-02	1.63E-04	1.34E+00	7.69E-09	1.45E-03	2.72E-03	2.99E+00	1.42E-04

3.3 Data Assessment

This analysis relies heavily on the emission factors for TRACI impacts published in the EcoInvent database. Each of these factors was used as published and unfortunately did not include any statistical analysis such as standard deviation. They were almost all assembled from sources in Europe, except for electricity generation (pumping, heating) were US data was available. All factors were used at plant, as desired, and do not include transportation to synthesis location or water treatment location. Good correlation between inventory items and described factors was generally found. For instance, specific chemicals with matching CAS numbers were identified in the database. One general anion exchange resin was used from the database, but synthesis procedures can vary widely and develop rapidly over time lending to low reliability. Titanium and iron ore factors also vary based on production process and using a single data point has low reliability.

Further assessment of the data is provided in a pedigree matrix in Table 2. Six sets of data were evaluated for reliability and sensitivity. Because the resin is a high impact for both resins, the methanol is a high impact for the Fe-WBAX, and the heating electricity is a high impact for the Ti-WBAX, they were each chosen to be evaluated. The inventory data and the impact factor data were evaluated separately for each. A score of 1 indicates the data has high reliability or sensitivity, and a score of 5 indicates very low reliability or sensitivity.

Table 2

Criteria	Resin Inventory	Methanol Inventory	Electricity Inventory	Resin Impact Factors	Methanol Impact Factors	Electricity Impact Factors	Comments
Impact on Final Result	1	2	2	1	2	2	These are the most important contributions to the final results. Resin contributes to both, while methanol is unique to Fe-WBAX and electricity is unique to Ti-WBAX
Acquisition Method	1	1	1	3	3	3	Inventory data measured, but impact assessment data comes from database with built in assumptions.
Independence of Data Supplier	1	1	1	1	1	1	No invested commercial venture contributed data to this study
Representation	5	5	5	1	1	1	Inventory data collected from a single site over small period, with unexplored temporal or geographical variations. Impact assessment data is largely national averages studied for more than one year.
Temporal Correlation	1	1	1	4	4	3	Inventory data is from recently developed methods. Impact assessment data is from the 2010 database, but were actually collected between 1994-2004.
Geographical Correlation	1	1	1	3	4	2	Inventory data is from locally developed methods. Impact assessment data is largely European averages, except for electricity which is US average.
Technological Correlation	1	1	1	3	3	2	Though the methanol production process has not drastically changed, adoption of underground natural gas mining has likely changed acquisition of raw material for it. This resin is for a type 1 strong base anion exchange resin of polystyrene and divinylbenzene crosslinking which is a common method, but other widely varied technologies exist. Electricity generation technology has not drastically changed.
Range of Variation	5	5	5	5	5	5	Inventory is likely to vary widely as the technology is optimized and scaled to commercial production.

3.4 Proposed Future Work

Future work can aim to further refine this study and to expand it to include other water treatment options. Proposed future work for this study before peer reviewed publication or use in a dissertation includes:

- Statistical analysis of the data, including distribution and Monte Carlo simulation to give larger confidence in the data.
- Quantify human toxicity and carcinogenicity avoided by removing contaminants. Water treatment is intended to lower the overall health risk after all.
- LCA of mixed bed. The alternate technology to using the hybrid resins is to use two different sorbents with individual capacity for pollutant removal. This will be included as a third option for comparison.
- Modify inventory to account for metal precursor reuse. For either of these hybrid resins the metal precursor is a very high concentration solution that is reusable for multiple resin batches. Recycle of this precursor solution should be allocated to a single batch of resin.
- Include additional impacts partial to a hazardous waste classification during the disposal phase if necessary.
- Compare to impacts from water distribution pumping, or resin hauling. If those impacts are orders of magnitude higher than those found here, it can be said that the treatment step is negligible and small preferences between the two resins will be trivial.
- Identity what process in the synthesis of the parent anion exchange resin has such a high ozone depletion potential and study if this process can be avoided.

4. CONCLUSIONS

The Ti-WBAX resin is the environmentally preferable option for simultaneous treatment of Cr and As in terms of eutrophication potential, global warming potential, ozone depletion, and human carcinogenic potential. The Fe-WBAX is the environmentally preferable option in terms of acidification potential, ecotoxicity, and human respiratory effects. Their impacts are very similar in terms of photochemical oxidation and human non-carcinogenic toxicity.

Electricity use for oven heating during the synthesis of Ti-WBAX is one of the largest contributor to environmental impacts and one of the largest opportunities for reducing those impacts. Resin manufacturers can help mitigate these impacts through utilizing high efficiency ovens and verifying full use of oven capacity each time a batch is synthesized.

Sulfuric acid and sodium chloride post treatments used in the synthesis process have small impacts compared to the parent anion exchange resin itself. Optimizing their use to maximize pollutant removal capacity may be beneficial from an environmental standpoint if it reduces the total mass of resin needed to treat a given volume of water.

Regulators who set water quality standards usually do so in an effort to reduce human exposure to negative health effects. While lower exposure to contaminants such as Cr and As will reduce these risks overall, employing additional treatment technologies will add other environmental impacts. Tradeoffs between human health impacts and environmental impacts should be understood in considering new water quality regulations.

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