Solutions for Sewage Sludge Reclamation and Plastic Waste Reduction

by

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ABSTRACT

This thesis examines the composition, flow rate, and recyclability of two abundant materials generated in modern society: municipal sewage sludge (SS) generated during conventional wastewater treatment, and single-use plastic packaging (specifically, plastic bottles) manufactured and dispersed by fast-moving consumer goods companies (FMCG). The study found the presence of 5 precious metals in both American and Chinese sewage sludges. 13 rare elements were found in American sewage sludge while 14 were found in Chinese sewage sludge. Modeling results indicated 251 to 282 million metric tons (MMT) of SS from 2022 to 2050, estimated to contain some 6.8 ± 0.5 MMT of valuable elements in the USA, the reclamation of which is valued at $24B ± $1.6B USD. China is predicted to produce between 819 - 910 MMT of SS between 2022 and 2050 containing an estimated 14.9 ± 1.7 MMT of valuable elements worth a cumulative amount of $94B ± 20B (Chapter 2 and 3). The 4th chapter modeled how much plastic waste Coca-Cola, PespiCo and Nestlé produced and globally dispersed in 21 years: namely an estimated 126 MMT ± 8.7 MMT of plastic. Some 15.6 MMT ± 1.3 MMT (12%) is projected to have become aquatic pollution costing estimated at $286B USD. Some 58 ± 5 MMT or 46% of the total mass were estimated to result in terrestrial plastic pollution, with only minor amounts of 9.9 ± 0.7 MMT, deemed actually recycled. Absent of change, the three companies are predicted to generate an additional 330 ± 15 MMT of plastic by 2050, thereby creating estimated externalities of $8 ± 0.4 trillion USD. The analysis suggests that a small subset of FMCG companies are well positioned to change the current trajectory of global plastic pollution and ocean plastic littering. Chapter 5 examined the barriers to Circular Economy. In an increasingly uncertain post pandemic world, it is becoming progressively important to

conserve local resources and extract value from materials that are currently interpreted a "waste" rather than a current or potential future resource.

DEDICATION

This thesis is dedicated to my mother, Kalavathi, and my father, Rengarajan.

You came to Vienna with nothing, and you gave me everything.

You are the best parents in the world.

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CHAPTER 1

INTRODUCTION

Before the year 2020, nearly two thirds of food, minerals, and fossil fuel we grew and mined ended up as waste (Kaza et al., 2018). I write this introduction in a world altered by a tiny genetic fragment, to impact commerce and global economic markets rapidly and lastingly. Many things taken for granted before the pandemic, from the ready availability of toilet paper, food, batteries, and water bottles, suddenly became prime commodity. Many supply chains came to an abrupt halt, affecting stock prices, demand for commodities, and material inventories of businesses. Nearly every single element mined, from steelmaking (iron ore), energy (thermal coal, uranium), electric-vehicle battery (cobalt, lithium, nickel), fertilizer (phosphate rock, potash) to precious metals (gold), experienced a decline in average monthly production (Azevedo et al., 2020). Multinational companies discovered that a global supply chain represented a severe liability to growth (Forbes, 2021). Many cities throughout America found themselves without suitable avenues to import plastic material for packaging their products, leaving the shelves of many groceries stores empty (New York Times, 2022). Beverage companies in particular suffered the most, due to the lack of local Polyethylene Terephthalate (PET) bottling options, and all this while nearby landfills reached their maximum capacity prematurely, up prematurely, triggered by vast amounts of plastic, paper, metal, and glass; resources at the wrong time in the wrong place, turning into a liability and waste. The irony between the starved supply chains and proliferating waste streams was bitter.

With this thesis, I seek to challenge the meaning of “waste” in a post pandemic world. Is waste still a concept humanity is entitled to believe in, perpetuate and inflict on itself. Peter Zeihan (2022) called the pandemic the beginning of the end of globalization. In the grand scheme of things, China was the quintessential producer and America the relentless consumer, with the rest of the world's countries falling somewhere in the middle. Against the backdrop of the struggling world economy, this thesis looks at two classes of abundant materials that could be classified either as a polluting waste or as a resource, depending solely on where they are located, and whether and how they are collected, sorted, and treated and disposed of: sewage sludge (SS), which represents the unwanted byproduct of conventional wastewater treatment using activate sludge technology, and single-use plastics.

1 Research Outline Summary

The goals of this thesis were (i) to examine sewage sludge as an underutilized resource of metals used in modern society, and (ii) to elucidate the problem of global pollution with single-use plastic waste with a sub-aim of identifying within the fast-moving consumer goods (FMCG) marketplace previously unexplored yet promising intervention points to turn the tide on the global plastic pollution crisis. The first half of this thesis (Chapters 2 and 3) represent laboratory work, conducted by me with the help of a team of collaborators, focusing on inventorying the types and concentrations of some 60 elements in U.S. and Chinese sewage sludge, with an emphasis on metals. The latter half of the thesis (Chapters 3) documents the use of secondary data analysis and modeling of big data sets sourced from corporate plastic inventories, specifically the PepsiCo, Nestle and Coca-Cola corporations, that jointly represent some 85% of the worlds beverage market (REF). Relying on production and sales data from the last two decades, I analyzed the material flows of packaging plastics from these three multinational beverage companies and investigated the global movement of FMCG products as well as their ultimate end-of-life sinks. The final chapter (Chapter 5) represents a more philosophical examination of the definition of waste and who is responsible for it. In my analyses, two analytical frameworks were helpful in informing the interpretation of the data collected in this work: (i) the Circular Economy (CE) Framework and (ii) the Waste Management Hierarchy (WMH).

1.1 Analytical Frameworks

1.1.1 Circular Economy (CE)

The fundamental aim of CE is to design a materials and value chain that is void of waste (EMF, 2012). While the Ellen MacArthur Foundation (EMF) provided a major jolt in the global popularity of the CE concept in 2013, the framework goes back in time and has been influenced by the works of Pearce and Turner (1989), cradle to cradle McDonough and Baungart (2002), industrial ecology Graedel and Allenby (1995), biomimicry (Benyus, 2002), and closed loop industrial economics (Stahel and Reday, 1976). The CE concept endorses a closed loop material flow paradigm for the global economic system, that is "restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times" (Ellen MacArthur Foundation, 2014). The more rigorous academic definition coined by Geissdoerfer et al., (2017), calls out CE as "a regenerative system in which resource input and waste, emission, and energy leakages are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." The Netherlands, France and Germany have been among the first countries to integrate CE into their legislation and bilateral waste laws as early as 1996 (Domenech, T., & Bahn-Walkowiak, B. 2019). Japan along with the Europe Commission soon followed suit, predominantly by economically incentivizing waste reduction in any form. A notable example comes from Denmark where 11 industries situated side by side synergistically harmonized their interactions by adopting a material or energetic output (and potential waste stream) as a resource, saving all involved some $27M USD in 2019 (M. Chertow & Ehrenfeld, 2012; M. R. Chertow, 2008; Christensen et al., 2014). While being popular and well-intended, some industry stakeholders adopt a 'green' socio-political model with both hesitancy and skepticism, and the general public tends to scrutinize proclaimed ambitions and progress for evidence of greenwashing of business-as-usual agendas. Companies like the Dow Chemical Company (TDCC) endorse CE, while not necessarily taking great strides toward truly minimizing their ecological footprint (Goldberg, 2020). In 2018, FMCG companies such as The Coca-Cola company, Mars, Walmart, Unilever, PepsiCo, and Nestlé became part of the EMF foundation to form, "a coalition of leaders to create circular economy for plastics." It was at the insistence of the EMF, that PepsiCo, Coca-Cola, and Nestlé disclosed their plastic consumption that laid the foundation for Chapter 4 of this thesis. Ultimately, the EMF functions as a liaison between industry, governments, policymakers at all levels endorsing the end of a linear economy. To what extent they are making strides is subject to both evaluation and discussion.

1.1.2 Waste Management Hierarchy

The waste management hierarchy (WMH) was first introduced by the European Union’s Waste Framework Directive (Nugent et al., 2022) as a way to protect human health and the environment. It suggest that the consumption and use of every material must be *prevented* and *reduced* so that less of it ends up in waste streams. *Reuse* and *recycle* are the second steps in ensuring materials are kept in circulation instead of becoming obsolete. *Recover* pertains to recovering energy embedded in the product, before being finally *disposed* of, which is the least wanted outcome for human health and the environment. Ultimately it is conceived that the mass of the materials/ waste reduced as it travels down the WMH. Below, I analyze plastic and sewage sludge from the lens of the WMH.

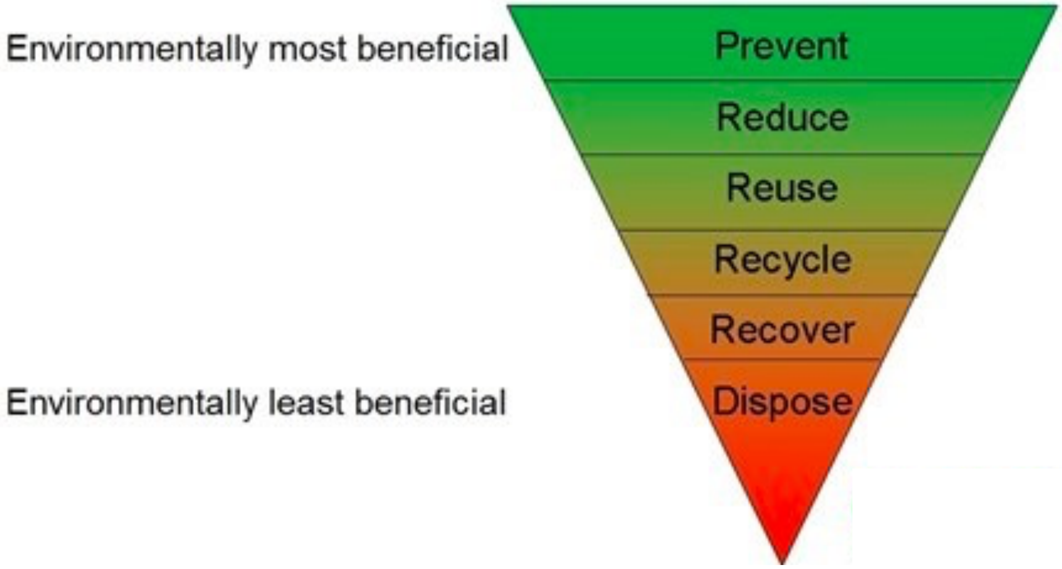

Figure 1. The Waste Management Hierarchy (Greenstep, 2022)

1.1.2.1 Prevent and Reduce

Reducing waste from a consumer standpoint means to refrain from buying, which is hard. In some countries “litterless” grocery stores have come up, that sell in bulk and the customer bring their own containers (Beitzen-Heineke et al., 2017). Reducing waste from an industry perspective means cutting out unnecessary material and energy expenses (lean management). Lauded examples of companies in the forefront of is Ray Anderson’s carpet tile company *Interface* that cut down 60% of its waste by employing biomimicry, industrial ecology, and lean management tools, saving some $400M USD in 2011 alone (Anderson & White, 2009). Other notable examples are Patagonia (an outdoor brand), that repairs used clothing from their brand for customers, and shoe company Allbirds; that use excess wool to make shoes that would otherwise be wasted.

1.1.2.2 Reuse & Recycling

Collecting materials separately for recycling is the norm in the EU, where clear glass, colored glass, paper, metal, and plastics are collected separately. Developing countries, including China and India have a robust informal waste worker system, in which laborers separate valuable materials from disposal streams including household refuse. Research has shown that informal waste pickers save cities and municipalities up to $40M USD per year (Baud, 2004; Scheinberg et al., 2010). In the U.S. American context, the landscape is different and activities more diverse. Waste management and sorting practices differ by state, with some states collecting materials separately but most collecting what is referred to as “mixed recycling”. In general, mixed solid waste recycling results in contaminated outputs (recycled resources) decreasing the market value of a recycling bale. On average plastic recycling bales have a material purity level of 85%, while manufacturing industries need a manufacturing purity grade of 99% in order to not compromise their products and value chains (Antonopoulos et al., 2021; Lase et al., 2022; Roithner & Rechberger, 2020). This is the reason for the widespread phenomenon of ‘*downcycling*’ of plastics, of creating with a significant investment a segregated flow of materials that ultimately do not have a viable customer to enable successful and impactful closed loop recycling. While recycling bales composed of aluminum and metal typically faring relatively better in their purity grades, it is still uncertain how much of the aluminum mass that is put out into the market annually in the USA is actually recovered and reused.

1.1.2.3 Recovery

Recovery of value streams and particularly the recovery of energy is central to the WMH framework. More developed countries may be perceived as leading in this area, as a superior infrastructure enables them to limit the water content of their waste streams, thereby maximizing the potential for recovery of the calorific value embedded therein. In the context of this thesis, maintaining and reducing the water content of material flows is particularly important for sewage sludge, whose original water content of ~95% in many developed countries is reduced via pre-treatment to 63% (Pinnekamp, 1988), actions that accomplish both a reduction in waste volume and a stabilization of this rich organic material that otherwise is known to give off large amounts of noxious volatile chemicals known to harm ecosystems, the atmosphere and human health. The incineration of one metric ton of solid waste typically leads to a ~70% reduction in weight and a ~90% reduction in volume (Doberl et al., 2002). Optimizing waste incineration and energy recovery also requires a tight control of emissions including products of incomplete combustion such as (Sulphur oxides, nitrogen oxides, carbon, and carbon monoxide etc)

(Raheem et al., 2018). With the advancement of sophisticated scrubber systems, most waste incineration plants within the EU only emit water vapor, thereby complying with stringent environmental air quality regulations (Davis & Hall, 1997; Inglezakis, Zorpas, Karagiannidis, et al., 2011). In the USA in contrast, the recovery of energy from the incineration of waste (including sewage sludge) is less common or even disincentive or prohibited. As of 2019, there were just 86 solid waste incinerators in the USA, whereas the EU operates some 455 (EPA, 2021). Energy recovery of waste in the USA is not expected to increase significantly due to public sentiment toward incineration, the current state of public opinion and the prevailing geopolitical agendas. Hence, landfilling of solid and sludge waste represents the preferred method of waste disposal in the USA (EPA, 2021).

1.1.2.4 Disposal: Landfilling

Most countries that are part of the EU has stringent landfill directive that prohibit the burying of waste featuring an organic content of greater 5% by weight. Therefore, much of Europe incinerates waste and then landfills only the retained fly and bottom ashes (Allesch & Brunner, n.d.; Austria, 2000). In conjunction with the *green dot program* in Germany and the Alstoff Recycling Austria company, the WMH has achieved some notable successes in reducing, reusing, recycling, and recovering materials and particularly energy before landfilling of residual ashes (Wilson, 1996). In recent years many European cities have resorted to extracting metal from their incinerator ashes before landfilling them, essentially mining “waste” before it become landfilled. In the EU all landfills are property of the state with distinct public-private partnership contracts in place, so that private companies are contracted for operation and maintaince only. Thus, the landfill tipping fee is collected by the government, thereby removing a potential perceived economic incentive for any one actor in the waste system to produce more rather than less waste (Gelbmann, 2008; Lebensministarium, 2011). In America, the situation is completely different partially because land is plentiful, and many landfills are owned and operated privately. Here, private ownership of landfills creates a powerful incentive for depositing more waste to increase profits. The more waste the US society at large creates, the more profits are being realized by landfill owners. In the USA most of the landfill composition is exactly as discarded in the black bin: roughly 23% cardboard, 21% organic and miscellaneous, 12% plastic, 8.8% metal, and 4.2% glass (EPA, 2021). There is no discrimination as to what materials are deposited in landfills. Often the waste of industries and households is mixed, causing so-called *red field sites* of potential concern (EPA, 2021), if the landfill is not properly maintained. Furthermore, landfills often are situated on Native American lands, where federal and state landfill regulations are not applicable and where the deposition then can be even more lucrative but also more polluting.

1.2 Metals

Mined metals are crucial to the modern world. Much of consumer technology used today from cell phones to laptops, uses cobalt, neodymium, nickel, copper, tantalum, aluminum, gallium, and zirconium to name a few. In 2022, the USA listed platinum, rhodium and cesium as critical commodities, all metals used in the oil and gas industry (EPA, 2021). The consequences of mining metals today range from economic progress and improvements of quality of life of large populations to the degradation of environmental and human health as well the geopolitical unrest and even national security risks (Lynch et al., 2014).

The mining industry is a capital intensive, energy- and waste-intensive industry (Lynch et al., 2014). The negative *externalities* of mining include deforestation, erosion, contamination of rivers, streams, and wetlands as well as the contaminated or diminished soil quality, in addition to other pollution from noise sources, particulate matter, and GHG emissions (Sethi et al., 2006). Mining is known to have far ranging social consequences, including economic benefits that come with adverse impacts on wildlife, fauna, and human populations, particularly for traditional and native cultures. In 2017, Asia mined 9,962 MMT, North America mined 2,477 MMT, Europe mined 1,459 MMT, closely followed by Oceania with 1,199 MMT (Statista, 2022). Latin America mined 1,127, and Africa mined 966 MMT of resources in total (World Mining Data, 2019). There was a 97% and 132% increase, respectively, in Asian and Oceanic mining activities in 2017 compared to 2000. Europe experienced a 16% decrease compared to 2000, while other continental regions had a mining growth increase between 8.6% and 26% (Azevedo et al., 2020). The process of mining is tedious, technically challenging, and requires high capital expenses. Most readily minable locations globally have already been extracted, leaving more complex deposits to be exploited both on land and below the seas. The cost of extracting these hidden resources is substantial; the average mining infrastructure for extracting one MT of copper was $4000 - 5000 USD in 2000. Today, that number is estimated at above $12,000 USD/t (Mills, 2022).

Mining ore is just the first step to extracting metal. To be able to attain a pure grade of a metallic substance, mined metal ore typically needs to be heated to high temperatures of above 950 degrees Celsius to burn off unwanted comingling materials, before being subject to submersion in large vats of acid to strip away other minor impurities (Botin, 2009). Thus, mining is an extremely energy intensive and hazardous process, which is reflected in the price of pure metal even if the latter does not include all the externalities. In the case of precious metals like Platinum, the refining process may take up to seven months and can require as much as 300 kg of ore to make a single gram of Platinum, costing between $770 and $1,800 USD per ounce (Zientek et al., 2017). Mining 1 ounce of gold cost $162 USD in 2008. In 2021 that cost was $770 USD. In 2022, zinc composite costs increased by 24% compared to the cost in 2018, at $2985 USD/t (Statista, 2022).

During the pandemic, many supply chains came to an abrupt halt, affecting demand for commodities, stock prices, and material inventories of businesses. Nearly every single element mined, from steelmaking (iron ore), energy (thermal coal, uranium), electric-vehicle battery (cobalt, lithium, nickel), fertilizer (phosphate rock, potash) to precious metals (gold), experienced a decline in average monthly production (reference). Uranium fell nearly 47% of its global supply as Kazakhstan stopped production (Economist, 2022). Nickel, Zinc, Copper were down 21%, 19% and 15% compared to pre-pandemic production levels, while Gold, Lithium and Cobalt were down 10%, 9% and 12% respectively (Azevedo et al., 2020).

For metals to be a realistic and integral part of the circular economy at their end-of life stage, it is important to consider that their uses are diverse, with much of the in-use phase ranging from 1 to 10 years (Powell et al., 2016). In the EU, most electronics and food grade metals are collected separately, and the metals extracted (either locally or as part of electronic and material waste trade). Since all waste in the EU must be incinerated before entering landfills, the bottom ash after complete combustion is extracted further for metals, ensuring no metals entering landfills. This is not the case in the USA. Consumer and industry waste are often mixed together, including organic fractions, and sewage sludge, entering landfills as a messy heterogenous mix of materials. In 2017, China stopped accepting US waste fractions because they were contaminated to a degree that rendered their economic reuse impractical. This policy had several ramifications for local American municipalities and recycling facilities scrambling to be able to absorb and manage the excess waste (Brooks et al., 2018).

1.3 Plastics

Synthetic polymers started being produced en masse in the 1950s as a way to utilize a by-product of the petroleum/energy industrial complex. By the late 2000s, cheap fossil fuel-based consumer plastics had proliferated into nearly every aspect of modern life. Global plastic production in 1989 was 100 million metric tons (MMT) and by 2019 had reached 368 MMT (Geyer et al., 2017).

Table 1. Overview of the most common plastic types utilized around the world (Plastics Europe, 2013).

Type	*Abbreviation*	*Production in MMT*	*Worldwide Production %*	*Most Found in Water bodies (Rank)**
Polyethylene	PE	85	30	1
Polypropylene	PP	54	19	3
Polyvinyl chloride	PVC	31	11	-
Polystyrene	PS	21	7	4
Polyurethanes	PUR	21	7	-
Polyethylene terephthalate	PET	19	7	2

*
(Source: Law et al., 2014, Gewert et al., 2015; Van Sebille et al., 2015; Lebreton, 2017)

Plastics used in the building and construction industry have long life spans, ranging from 5 to 30 years (Geyer et al., 2017). The shortest useful life span of plastic products includes single use plastic packaging. Plastics started to replace glass globally in the beverage industry in the 1990s (Welle, 2011). Since then, the most prolific plastics are polypropylene (PP) and PET. Both polymers cannot be infinitely recycled, and both require a blending of new and reused polymers at a ratio of at least a 20 to 50% virgin plastic for the use of PET bottles, for example (Gomes et al., 2019). But more than that, the very concept of recycling is nuanced. Recycling is a conglomeration of actions that can look very different for different materials. For most plastics, the process starts with collecting, sorting, cleaning, washing, bailing, chipping, and melting before it is finally sold to manufacturing industries, depending on their purity grade (Medina, 2002; Morlok et al., 2017). Furthermore, the notion of something being "recyclable" is often a function of location geography and of the end markets, rather than an inherent judgement on the material itself and its intrinsic values. Business Insider (2022) recently ran a story that elucidated the point clearly, saying "your widely recyclable plastic yogurt container is rarely recycled." The material is technically 'recyclable' but EPA data shows that only 2.7% of PP actually is recycled (EPA, 2021). This goes back to the fact that a successful recycling process often is constituted of a large number of separate sequential actions that all cities and states usually do not have the capability nor the economic resources to recycle all the material output streams they create. This is why waste is often traded, locally and internationally. Seeing that both plastic polymers and valuable elements are often wasted and lack recycling pathways, the next section looks at the specific research questions associated with understanding metals and elements in sewage sludge and plastics in this dissertation.

1.4 Sewage Sludge from the USA

1.4.1 Primary Research Questions.

i) What are the elements present in sewage sludge in USA?
ii) What are the ratios of elements found in sewage sludge in the four regions of the USA?
iii) Are there differences in the elemental composition of U.S. sewage sludges produced in 2001 versus 2016?

iv) Which elements are in sewage sludge from the USA occur at levels significantly enriched over levels found in the upper crust of the Earth?

v) What is the anticipated inventory of sewage sludges in the USA year-by-year up to the year 2050?

vi) What is the anticipated inventory and value of elements extant in sewage sludge through the year 2050?

vii) What is the anticipated value of the elements extant in sewage sludge through the year 2050?

Guiding Hypothesis. Significant changes have taken place in the U.S. industrial complex, in the consumer product spectrum, and in consumer behavior. Hence, I hypothesize that an elemental analysis of U.S. sewage sludge will show a statistically significant ($p<0.05$) differences in the mean concentrations of elements detectable in samples collected in 2001 versus samples collected in 2015.

1.5 Sewage Sludge China

1.5.1 Primary Research Questions.

i) What are the elements present in sewage sludge in China?

ii) Are there differences in the elemental composition between sewage sludges produced in China versus USA?

iii) Which elements are in sewage sludge from the China occur at levels significantly enriched over levels found in the upper crust of the Earth?

iv) What is the anticipated inventory of sewage sludges in the China year-by-year up to the year 2050?

v) What is the anticipated inventory and value of elements extant in sewage sludge through the year 2050?

vi) What is the anticipated value of the elements extant in sewage sludge through the year 2050?

Guiding Hypothesis. Significant changes have taken place in China's industrial complex, in the consumer product spectrum, and in consumer behavior. Hence, I hypothesize that an elemental analysis of Chinese sewage sludge will show a statistically significant ($p<0.05$) differences in the mean concentrations of elements detectable in samples collected in China versus samples collected in the USA.

1.6 Primary Objectives and Hypothesis: Plastics

i) How much plastic (in MT) have Pepsi, Coke, and Nestle made in the past 20 years?

ii) How much plastic (in MT) are Pepsi, Coke and Nestle forecasted to make in the future till 2050?

iii) What is the cumulative mass of plastic (in MT), amassed in the last 20 years, in each of the 185 global countries that is attributable to Pepsi, Coke and Nestle?

iv) What is the cumulative mass of plastic (in MT), amassed in the last 20 years, in each of the 6 global end-of-life sinks that is attributable to Pepsi, Coke and Nestle?

v) What is the cost to taxpayer of the associated plastic waste that is directly created by Pepsi, Coke and Nestle?

1.7 Barriers to Circular Economy

i) What are the main systemic barriers to circular economy becoming a reality at scale?

TRANSITION 1

Many elements are mined to enable everything in our modern lives, such as Zinc, Copper, Iron, Lead, Silver, Gold and Phosphorous. Mining each of these elements is an energy intensive process, costing many millions of dollars. For all the elements we mine, all of it either remains in use, becomes solid waste, or ends up in the liquid waste fraction. The liquid fraction of waste has a solid component to it; namely biosolids, or otherwise known as sewage sludge. Sewage sludge is the by-product of the wastewater treatment industry, rich in organic content, but known to contain high concentrations of heavy metals. Studies have been sparse to characterize the latent value of embedded in sewage sludge, looking at it like a resource rather than a waste. The following chapter tests for the presence of 60 elements in sewage sludge, how much of those elements are sequestered in sewage sludge, particularly from sludge samples from the USA. The estimated amount of sewage sludge that USA is expected to produce annually is also modelled. To conclude the latent value of the elements found in sewage sludge is calculated and addressed.

CHAPTER 2

CHEMICAL ASSESSMENT AND FUTURE VALUATION OF ELEMENTAL RESOURCES IN U.S SEWAGE SLUDGE THROUGH THE YEAR 2050 ABSTRACT

ABSTRACT

Very few studies have looked at characterizing the latent, mostly untapped economic value of metals and other elemental constituents in U.S. sewage sludge, whose disposal costs American taxpayers an estimated 482 $M annually. Research on untreated sewage sludge and treated sewage sludge deemed fit for application on land (biosolids) has mostly focused on the potential risks that metals and other sludge constituents pose to ecosystems, wildlife, and human health. In this laboratory and modelling study, we analysed by ICP-MS dried sewage sludge collected in 2015/16 from 23 U.S. cities, created a comprehensive elemental inventory of U.S. municipal sewage sludge, and forecasted its monetary value through the year 2050. Among 60 elements targeted, 55 were detected. A total of 33 industrial elements (i.e., Fe, P, Zn, Cr, Mn, Cu), 5 precious elements (e.g., Gg, Pd, Au, Ru, Pt), and 13 rare elements (e.g., Ce, Pr, Tm, Lu) were detected. Industrial elements occurred at the highest concentrations from 10^1 - 10^5 mg/kg dry weight (dw). Precious and rare elements were found in the range of 10^{-3} and 10^1 mg/kg dw. The Midwest and Southwest had the highest concentrations of valuable elements, while levels in the American West and Northeast were lower. Concentrations of Cd, Ru, Ag, Mn, Ti were 10 - to 71-fold higher than those reported for 2001. Palladium levels had doubled ($p < 0.05$); Re was detected for the first time. Rare elements as a whole category, were three-times higher in concentration in 2001 than in 2015. Elements significantly enriched over levels

in the Earth's crust included (Te, P, Zn, Cr, Co, Ni, Pb, Sn, As, Sb, Mo, Cd, Re and B), and five precious elements (Ag, Pd, Au, Ru, Pt). The USA is estimated to produce between 251 and 282 million metric tons (MMT) of sewage sludge between 2022 and 2050, containing an estimated 6.8 ± 0.5 MMT of valuable elements. Future reclamation of these elemental resources would be profitable if performed at a cost of <$24B ± $1.6B USD and could be aided today by separating SS from household waste in landfills.

2 Introduction

Population growth and the need for adequate sanitation and a safe water supply have made wastewater treatment plants (WWTP) a necessary feature of modern civilization worldwide. A byproduct of conventional activated sludge wastewater treatment is excess sewage sludge from primary and secondary clarification requiring disposal. In the USA the number of WWTPs has grown significantly over the past three decades, increasing sludge production from 7.77 million metric tons (MMT) in 1988 to around 12.59 MMT annually by the latest estimates (Seiple et al., 2017a).

As more of the world increasingly becomes connected to centralized wastewater treatment systems, the amount of sludge produced is also exponentially increasing. Particularly in the USA the number of WWTP has risen from about 5,000 in 1988 to 15,014 in 2017 (Adhikari et al, 2020). The physical treatment, stabilization, transport, and safe disposal of sludge is time consuming and costly, making the handling of sewage sludge one of the most significant environmental and economic challenges in modern wastewater management. Sludge disposal has been the bane of WWTP operators for many reasons, costing anywhere from 40 to 60% of total plant costs, depending on size infrastructure (Murray et al., 2008). Before 1988 most of the sewage sludge was disposed of by dumping the unwanted materials mostly into the Atlantic Ocean. After the 1988 EPA ban on this practice, land application of sewage sludge has been the primary means of disposal, accounting for about 55% of all sewage sludge produced in the USA (Clarke & Smith, 2011). Land application requires additional treatment steps to transform sewage sludge into so-called biosolids deemed fit for application on land. (EPA 503b, 2019).

Whereas sewage sludge is most frequently analysed to better understand its potential toxicity on human health and ecosystems (Chang et al. 2001; Clarke and Smith 2011; Venkatesan et al. 2016), this currently unwanted material also constitutes a potential resource of valuable elements (Mulchandani & Westerhoff, 2016; Raheem et al., 2018; Seiple et al., 2017b). A study of archived U.S. sewage sludge collected two decades ago identified 14 elements in sewage sludge (Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) valued at $280/ton in 2015 USD (Westerhoff et al., 2015a). In the present work, we analysed by ICP-MS, a set of U.S. sewage sludge samples more representative of current day composition, compared them to prior observations, and further estimated the latent economic value of a broader set of elemental resources sequestered in U.S. sewage sludge through the year 2050.

2.1 Materials and Methods

Dried sludge samples were obtained in 2015 from 23 wastewater treatment plants from 23 U.S. cities located in 11 states (AZ, CA, CO, CT, FL, IL, KS, NV, OH, SD, WA). The sludge samples were dried and stored at -20 degrees Celsius as part of the Human Health Observatory sample archive located at the Center for Environmental Health Engineering at the Biodesign Institute in Tempe, Arizona, USA.

2.1.1 Materials and Reagents

The preparation, digestion and analysis of the dry SS was undertaken by the W.M Keck Foundation Laboratory for Environmental Biogeochemistry, a metal-free lab, with Ultra-Low Penetration Air (ULPA) filtered Class 10 laminar flow/exhaust workspace for ultra clean sample preparation and acid distillation, maintained at a Class 10,000 conditions for quality control and assurance, specifically designed to test trace elements. All reagents used in sample digestion or chemical purifications are trace metal grade or better. Reagents used in the preparation of the samples were trace grade or better. The water utilized in cleaning lab material and making all regents were obtained from a dedicated ultrapure 18.2 Ω water system supplied throughout the laboratory. More information in SI.

2.1.2 Sample digestion and elemental analysis

Samples were 1) ashed in ceramic crucibles at 550°C overnight to degrade organic matter and make the multi-acid digestion procedure more effective. This was followed by 2) an overnight pre-digest with nitric acid to prevent uncontrolled reactions during the microwave digest. The pre-digest was followed by 3) a microwave digestion in Mars 5 microwave system and completed by 4) repeated multi-acid hot plate digestions for maximum solubilization of solid material. 5) Samples were centrifuged to separate any small amount of residual solid, and 6) samples were then diluted for analysis by ICP-MS, in a modification of (Westerhoff et al., 2015). Hydrofluoric acid was not used, because the goals of this research were to determine the metals available for recovery in industrial processing. Although hydrofluoric acid would have improved the total metal recovery by degrading any silica tetrahedra present in mineral material, it would substantially increase the cost and hazard when scaling up any recovery processes. Details of each step are below.

Approximately 0.150 g of dried sludge sample was heated in a ceramic crucible to 550°C for 12 hours using a Thermolyne™ Tabletop Muffle Furnace (Thermo Scientific, Waltham, MA). Samples were then transferred to Teflon microwave digestion vessels with minimal amounts of 18.2 MW water to minimize sample loss. In order to prevent highly exothermic, uncontrolled reactions that could cause sample loss in the microwave, samples were "predigested" with 3 mL of 16 M HNO3, added in small increments while monitoring any foaming reactions. Samples were left to degas and react overnight in a laminar air-flow hood. Samples were then microwave digested using a MARS 5 with an additional 4 mL of 16 M HNO3 and 1 ml of 12 M HCl. The microwave digestion profile is as follows: 20-minute ramp to 150°C, 15-minute ramp to 180°C, 30-minute hold at 180°C.

Post-microwave digestion, samples were transferred to Teflon digestion vessels (Savillex, USA, see details in Supplementary information), and dried in ULPA filtered air on a hot plate at 150°C in a laminar flow exhaust hood. Samples underwent hot plate digestion, alternating addition of an aqua regia acid solution (1 mL of 16 M HNO3 and 3 mL of 12 M HCL), followed by sample drying, with a reverse aqua regia acid solution (3 mL of 16 M HNO3 and 1 mL of 12 M HCl) followed by sample drying. This alternation of acid was repeated until there was no more solid material, or there was no decrease in the amount of material between steps.

Samples were then transferred to 15 mL metal-free centrifuge tubes (VWR tube 15 mL Metal-free, catalog #89049-170 VWR, Visalia, CA) and diluted to ~13.6 mL total volume 0.32 M HNO3 and 0.3 HCl. Samples were centrifuged at 2000 rotations per minute (rpm) for 5 minutes, the supernatant decanted and centrifuged for an additional 10 minutes at 6000 rpm. Supernatant aliquots of 0.25 mL were transferred and diluted to 15 mL total volume with a final molar concentration of 0.32 M HNO3 and 0.3 M HCl. For samples requiring additional dilution steps, 0.25 mL of the final dilution was transferred and diluted to a total volume of 5 mL, in a final molar concentration of 0.32 M HNO3 and 0.3 M HCl for ICP-MS analysis (ThermoFisher Scientific iCAP Q, with CCT option). The addition of HCl improved the stability of some elements such as platinum group elements, which are poorly soluble in nitric acid alone.

2.1.3 Sample Processing

The laboratory building requirements of this lab also stipulated a "minimal metal" construction, with the interior parts of the lab constructed of polypropylene, and minimal expose to metal. Approximately 0.150 g of dried sludge sample was heated in a ceramic crucible to 550°C for 12 hours using a Thermolyne™ Tabletop Muffle Furnace (Thermo Scientific, Location). Samples were then microwave digested using a MARS 5 with 4 mL of 16 M HNO_3 and 1ml of 12 M HCl. The microwave digestion profile is as follows: 20-minute ramp to 150°C, 15-minute ramp to 180°C, 30-minute hold at 180°C. Post-microwave digestion, samples were transferred to Teflon digestion vessels (Savillex, USA), and dried in ULPA filtered air on a hot plate at 150°C in a laminar flow exhaust hood. Samples underwent hot plate digestion, alternating addition of acid solution (1 mL of 16 M HNO_3 and 3 mL of 12 M HCL), followed by sample drying 11 to 15 times. The process was repeated 11 to 15 additional times with 3 mL of 16 M HNO_3 and 1 mL of 12 M HCl. Samples were then transferred to 15 mL metal-free centrifuge tubes (Company, location), and diluted to ~13.6 mL total volume 0.32 M HNO_3 and 0.3 HCl. Samples were centrifuged at 2000 rotations per minute (rpm) for 5 minutes, the supernatant decanted and centrifuged for an additional 10 minutes at 6000 rpm. Supernatant aliquots of 0.25 mL were transferred and diluted to 15 mL total volume with a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl. For samples requiring additionally dilution steps, 0.25 mL of the final dilution was transferred and diluted to a total volume of 5 mL, in a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl for ICP-MS analysis.

2.1.4 Inductively Coupled Plasma - Mass Spectrometry (ICP-MS)

Samples were analysed by quadrupole Inductively Coupled Plasma-Mass Spectrometry (ThermoFisher Scientific iCAP Q, with CCT option). The instrument was tested for stability and sensitivity in a variety of ways, as well as approved for oxide production ratio and doubly charged production ratio before each sample was measured. The instrument passed mass and cross calibration and daily performance reports standards, which is important to the accuracy and precision of the data. Calibration standards were made up from single element certified ICP solutions. An internal standard solution of 100 ppb Sc, Y, In, and Bi was added by a second line into all measured solutions (blanks, standards, and samples) and was used to monitor and correct for potential instrument changes over time in the form of sensitivity drift and plasma suppression. Check standards and blanks were measured every six samples. Samples were typically measured at multiple isotopes whenever possible to monitor for interferences, but only data from a single isotope are reported in the summary table. Even though the instrument could detect most isotopes of an element, the most abundant isotope, or the isotope with the lowest detection limit, was reported. For example, three masses of iron (^{54}Fe, ^{56}Fe and ^{57}Fe) were measured by the instrument. Given that the standard deviation of the concentrations measured at the three isotopes was generally less than 5%, only data from the most abundant isotope ^{56}Fe, with the lowest detection limit, are reported.

2.1.5 QA/QC

As quality control, certified standards are usually used. NIST 2782 Industrial Sludge Standard Reference Material were employed as the certified standard to verify accuracy and reproducibility. They were digested and analysed along with samples using the same methodology. Method validation was tested for accuracy and reproducibility by spiking samples six distinct samples with metals at similar concentrations to the biosolid samples for consistency of element recoveries and using process blanks in parallel with each batch of samples. Duplicates and triplicates were also run of specific samples to test for accuracy. The average recovery of the certified standard was 63% with the standard deviation of 8%. The average spike recovery was 67% with a 19% standard deviation. The average standard deviation for duplicates and triplicates was 14%.

2.1.6 Comparison Temporal USA Data

All the statistical tests were performed in the R software v.4.1.1. Elements were classified into groups (precious, rare, industrial and other) based on Suanon et al., (2017) classification on chemical elements (APPENDIX A, Table 1-4). Data found in this study was compared to SS elemental analysis from previous a pervious study (Westerhoff et al., 2015) conducted on sludge sampled collected in 2001 ($p<0.05$). Data was first assessed for normal distribution using the Shapiro-Wilk Normality test. Subsequently, a Kruskal-Wallis test was employed to look at differences in the mean concentration distributions between the two time periods. When the Kruskal-Wallis rank-sum test was found to be significant ($p < 0.05$), further analysis using a post hoc Dunn Test was done to know if there was a statistically significant difference in mean concentrations by year and by element. Subsequently, an effect size test was conducted to understand if year alone a predictor of difference in mean concentration between the two years was.

2.1.7 Enrichment Factor

Enrichment levels indicate the extent to which an element is concentrated in soil from anthropogenic sources (Barbieri, 2016; Muzerengi, 2017). The comparison of the tested element with the background concentration of the same element in soils is indicated by the Enrichment Factor. Background concentrations were obtained from World Atlas (2021). A positive value indicates the degree with each element is enriched in sludge, supporting the argument that enriched elements can potentially be extracted or mined from this matrix. An EF above 5 is considered significantly enriched (APPENDIX A, Table 5).

$$EF = \frac{(M/RE)_{SS}}{(\frac{M}{RE})_{Background}}$$

Where,

$$EF = Enrichment\ Factor$$

$$M/RE_{SS} = Concentration\ of\ Element\ in\ Sample\ (\frac{mg}{kg})$$

$$M/RE_{Background}$$

$$= Reference\ Concentration\ of\ Element\ sourced\ from\ Word\ Atlas\ (\frac{mg}{kg})$$

2.1.8 Sludge Volume Inventory

All the statistical tests were performed in the R software v.4.1.1. Population data was retrieved from the world bank (World Bank, 2021). Sludge production is estimated at 26 kg^{-1} capita^{-1} year (Westerhoff et al., 2015). Each year's population was multiplied by the sludge mass per capita per year to the get total sludge mass per year, shown by equation 1. The population forecast from the world bank included confidence intervals for confidence intervals which were also multiplied by the same factor to provide the lower and upper bounds of SS.

Equation 1.

$$P_n * \left(\frac{K_n}{1000}\right) = SS_n$$

Where,

$$P_n = Population\ at\ n\ year$$

$$K_n = Sewage\ sludge\ (kg)\ per\ capita\ at\ n\ year$$

$$SS_n = Sewage\ Sludge\ (metric\ t) at\ n\ year$$

2.1.9 Element Inventory

All the calculations were performed in the R software v.4.1.1. Having established the concentration of elements, the metric tonnage of elements sequestered in sludge in the past and in the future was calculated using equation 2.

Equation 2.

$$\sum_{i=1}^{n} M = SS_n * (\frac{C}{1000})$$

$$M = Mass\ of\ Element\ at\ n\ year\ (in\ metric\ t)$$

$$SS_n = Sewage\ Sludge\ (metric\ t)\ at\ n\ year$$

$$C = Concentration\ of\ element\ (kg^{-1}t)$$

$$i = Time\ (in\ years, 2022 - 2050)$$

2.1.10 Economic Value Analysis

The value of the elements was collected from various sources (Westerhoff et al., 2015) and using the equation 3.

Equation 3.

$$ZT = M_t * Z$$

Where,

$$M_t = Mass\ of\ element\ from\ 2022 - 2050\ (metric\ t^{-1}year)$$

$$Z = Price\ of\ element\ in\ (USD/t)$$

$$ZT = Total\ values\ in\ USD\ of\ that\ element\ accumilated$$

$$from\ (2022 - 2050\ in\ USD)$$

2.2 Results

2.2.1 Concentration Hierarchy and Geospatial Distributions

Sewage sludge has shown to contain a large spectrum of metals (n=55) at concentrations spanning ten orders of magnitude. Among the elements investigated, the elements found in from the highest concentrations ranging between 10^4 and 10^5 mg/kg, were iron, calcium, phosphorous, and aluminium (figure 2). Industrial elements were found in the highest concentrations (10^2 - 10^5) with the least standard deviation (figure 2), with precious and rare elements found in lower ranges (10^{-4}-10^1). Phosphorous was the only non-mental found deposited in sludge in higher concentrations. This is not surprising seeing that the sludge was collected from a mixture of industrial and domestic sources. Thus, any water usage in smelting and manufacturing operations were most likely to result in higher concentrations of these. Metals and transition metals featured strongly in the higher concentrations including copper, titanium, nickel, and tin, although all varied by an

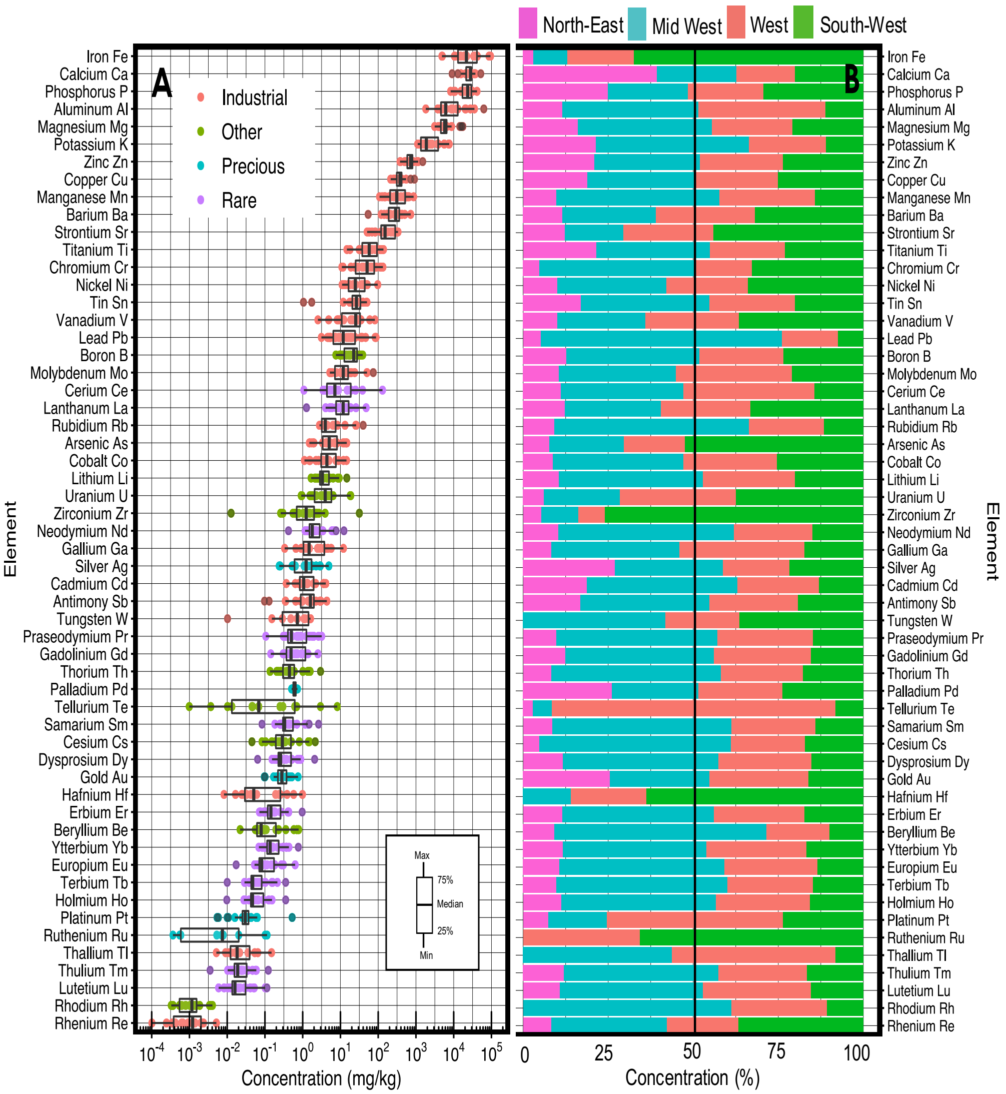

Figure 2. Box-Whisker rank order plot, organized by mean concentration of elements found in USA sewage sludge samples, collected in 2015/16, as determined by ICP-MS dry weight. A Whiskers are indicative of range and the box is indicative of highest and lowest quartile. Elements organized by decreasing mean concentration, while solid black line inside boxplots is indicative of median concentration. Dots are sample data points. Multiple sludge samples collected from 23 wastewater treatment plants from 23 cities in the USA in 2015. B The average of each element equating to 100%, with each of the

order of a magnitude (figure 1). Only one metal (thallium) was found in the lower concentrations (> 1). Beryllium, gold, and platinum were found in ranges between 1 and 0.01 mg/kg, indicating a presence of valuable elements in sewage sludge. rhenium, thulium, ruthenium, and holmium were found in concentrations between 1 and 0.001 mg/kg. The biggest variation and range can be observed for the element tellurium, hafnium, and ruthenium (figure 1). Overall, around 57 elements were found to be present in sewage sludge, many with economic value.

In panel B of figure 1, the samples were classified by geographic regions in the USA (north-east, mid-west, west and south-west). Samples collected in various parts of the USA exhibited different distributions of their concentrations. The north-east had the lowest concentration of elements (<25%), closely flowed by south-west (<28%). The mid-west had the highest concentration of elements (50%). The south-west accounted for over 60% of the distributions of iron, zirconium, hafnium, and ruthenium. ruthenium was only found in south-west and west of the USA. There was no rhodium, thallium, hafnium, and tungsten found in the north-east of the USA.

2.2.2 Comparing Temporal USA Data

Elemental levels detected here were statistically compared to available data published in 2015 for sludge samples collected in 2001 (Westerhoff et al.). The Shapiro-Wilk test for normality revealed that the data was non-parametrically distributed. Subsequently a Kruskal-Wallis test looked the differences in the mean concentration distributions between the two time periods and we found that there were statistically significant differences for 25 elements ($p < 0.05$) (APPENDIX A, TABLE 6). Further analysis using a post-hoc Dunn Test was done to know if there was a statistically significant difference in mean concentrations by year and by element (51 different overlapping elements). The Dunn test revealed that over 50% of the samples did not show statistically

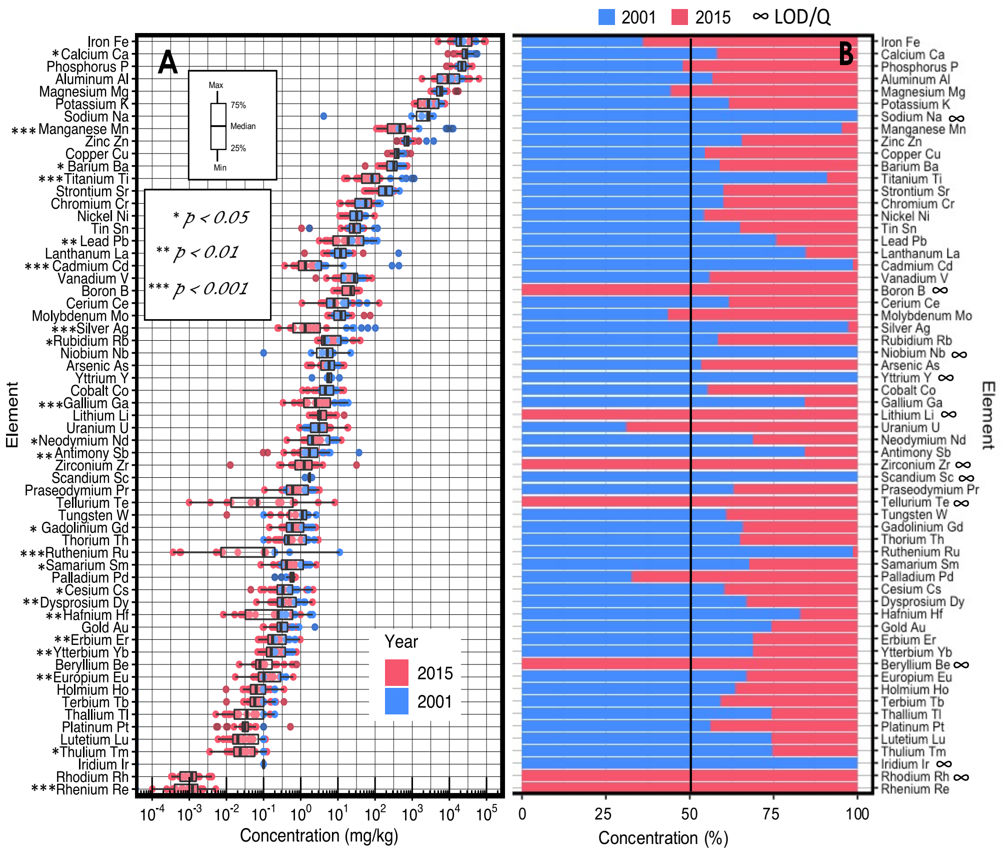

Figure 3. Comparison Box-Whisker rank order plot, organized by mean concentration of elements found in USA sewage sludge samples, collected in 2015/16 and 2000/01 as determined by ICP-MS dry weight. A Elements organized by decreasing mean concentration, while solid black line inside boxplots is indicative of median concentration. Dots are sample data points. Blue indicative of 2001 data and pink indicative of 2015 data. B Percentage distribution of each element between 2015 (pink) and 2001 (blue), as the percentage of total.

significant differences in their distributions at an alpha level of 0.05. Subsequently, an effect size test indicated that only 6% of the variation in mean concentrations could be explained by the sample year. This meant that while 50% of the samples did show a small difference in mean distribution by year, the year on its own cannot account for these differences (APPENDIX A, TABLE 6).

Most elements were observed to have a higher concentration in 2001 than they did in 2016 (figure 2 panel A). Rhenium was not found in samples test in 2001 and were found at concentration of 1.219x 10^{-3} mg/kg in 2016. Cadmium was found in concentrations 71 times higher in 2001. Ruthenium was found in concentration of 68 times higher than in 2001. Silver, manganese, titanium, gallium and were found in concentrations of 33, 20, 10, and 5 times higher than in 2001. Most elements were found in higher concentrations in 2001 than in 2016, with the exception of Palladium. Some elements were below LOD/Q in 2016, namely iridium, scandium, yttrium, and niobium. Others were not tested for in 2001 – such as rhodium, beryllium, tellurium and zirconium and thus, only 51 of the 55 elements overlapped between the two time periods (figure 2 panel B). By large, rare elements (e.g, Ce, Nd, Tm, Lu) had a statistically significant increase in the year 2001 ($p < 0.05$) and precious elements were 20 times higher in concentration (mg/kg) in 2001, than in 2016. At large 2001 data were higher in concentration.

2.2.3 Enrichment factor USA

An EF above 5 is considered highly enriched. In figure 3, Tellurium had the highest EF index, closely followed by Gold, Palladium, Ruthenium, Phosphorous and Silver. This indicates that these elements are concentrated in sewage sludge from anthropogenic activities, and we used only 2016 data for calculating these values. The least enriched elements are predominantly from the lanthanoid and the actinoid series, namely zirconium, titanium, beryllium. It was notable that predominantly precious and industrial elements

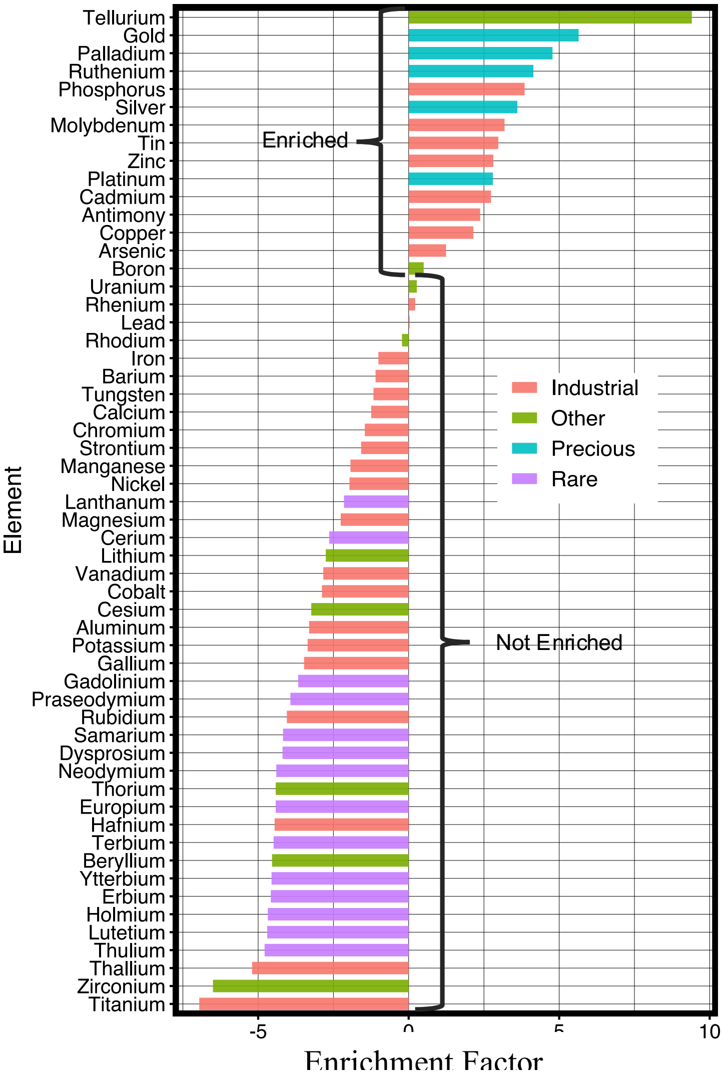

Figure 4. Elements enriched in U.S. sewage sludge relative to levels present in the Earth's crust. Eight industrial elements and five precious elements were enriched in sludge, suggesting opportunities for potential mining and resource reclamation.

were sequestered in sewage sludge. Tellurium is the only highly enriched metalloid, that was extremely enriched in SS, and it is interesting to note that this element was not tested for in 2001.

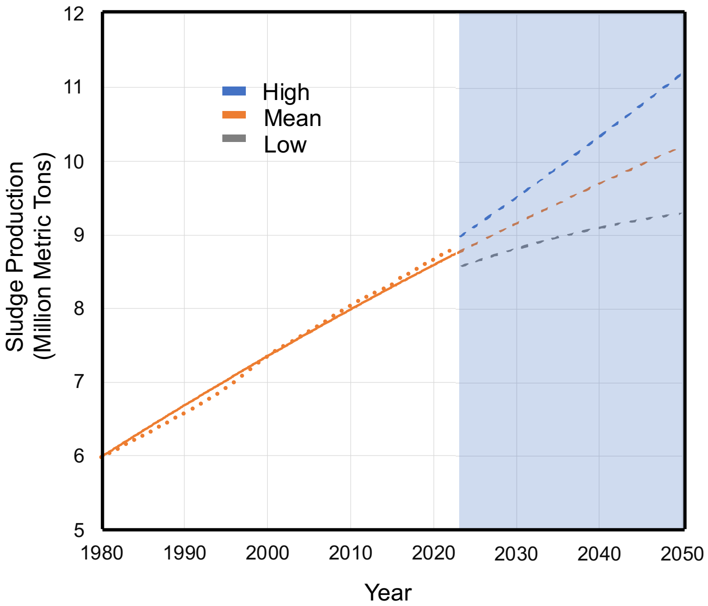

Figure 5. Predicting amount of sewage sludge in the USA from 2022 to 2050. Grey lines indicate high and low estimates based on US population trends, and yellow line indicated the average predicated tonnage by year. All estimates based on 26 kg-1 year. Shaded region is the future trend line extrapolated to 2050.

2.2.4 Inventory of Sewage Sludge Mass for USA till 2050

Sludge production went from 6 MMT to close to 9MMT in 40 years. The dark shaded are and the dashed lines represent predicted extensions of the past trend, based on USA population trends, and shows that SS is expected to increase from 8.8 MMT to 10.2 MMT by 2050, with the range expected to be from 9.2 to 11.2 MMT. So far, we have produced around 308 (± 32) MMT of sludge in the past and are likely to produce 275 (± 30) MMT in the future, without any changes in infrastructure and treatment processes.

2.2.5 Latent Mass of Valuable Elements in Sewage Sludge in USA

A total of 15 elements are highly accumulated in sewage sludge from now until 2050. Eight industrial elements and 4 precious elements. Phosphorous is expected to

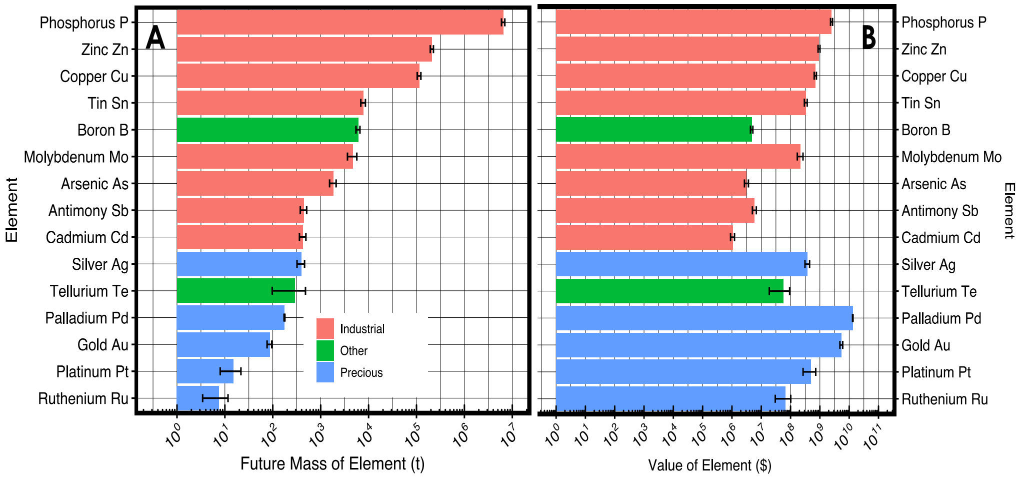

Figure 6. Mass and latent value of element accumulated in sewage sludge from USA from 2022-2050, based on samples collected in 2015/16. A Mass of each element accumulated in sewage sludge in 28 years in USA. B Latent cumulative value of in USD of all elements in sewage sludge in 28 years. 15 elements

accumulate at the highest mass with 6.4 (± 0.46) million MT, closely followed by Zinc and Copper at a mass between 209,704 (± 14,465) - 113,460 (± 8,994) MT (figure 5, panel A). Ruthenium and Platinum have the lowest mass aggregations over 28 years at 7.5 (±3.6) MT and 14.81 (±6.12) MT. The price per ton of Phosphorus, Zinc and Copper is 388, 4475 and 6181 USD-1 t respectively, accruing 2,508 million 938.4 million and 701.3 million USD in value in 28 years. Cadmium, Antimony, Arsenic and Boron are the only elements that accrue a cumulative value between 441,894 and 146,991 USD. Gold and Silver accrue a cumulative mass of 85 (± 8.5) and 390 (± 62.1) MT, which amount to a cumulative dollar value of 542.3 (± 60) million USD and 377.8 (± 37) million USD, respectively (figure 5, panel B). In total, 6.8 million MT of mass of elements, worth an estimated 24 (± 1.6) billion USD will be sequestered in sewage sludge from now till 2050 (figure 5).

2.3 Discussion

SS is a major by-product of treatment of wastewater. It is an increasing cost to municipalities and WWTP operators, there are a number of steps that they need to take to process and stabilize SS. The cost intensity the subsequent thickening, drying, dewatering, and stabilizing organic material by composting, digesting or heat treatment, account from anywhere from 40 to 60% of a WWTP operating costs (Cheremisinoff ,2019). The energy intensity of dewatering SS if one of the greatest challenges today.

In the USA 55% of SS is land applied in form called “biosolids”, regulated under the Title 40 code of Federal Regulations, Part 503, and 30% of SS is landfilled (Northeast Biosolids Associations, 2007). In addition to the energy intensity of stabilization, transporting SS add an even greater cost as SS has to be transported across multiple lines to for land application and landfilling. In recent years there has been a public backlash against land application because of strong odors, heavy metal contamination, hazardous organic compounds sequestered in SS and pathogens including antibiotic resistant bacteria. 37 of the 50 US states either ban land application of SS or impose strict regulations, requiring testing for and limiting pathogens and pollutants, on top of the federal limits (EPA Biosolids, 2021). In our calculations, the fraction of past 20 years of mass (MMT) of sewage sludge was approximately 7.1 MMT of metals was deposited in US lands, either in land application or landfilled. The fact that arsenic, antimony, and boron might have been present in land applied sludge, albeit in lower concentrations is indicative of why sludge increasingly stopped being applied to agricultural land (Cieŝlik et al., 2015). Increasingly, micro plastics have also been detected in SS.

In looking at SS through the lens of the WMH (Waste Management Hierarchy), sludge reduction is a double edge sword. SS is a by-product of many WWT trains, including biological nitrification, denitrification and enhanced phosphorous removal – all of which increase biomass of SS, while at the same time extracting valuable nutrients from waste.

It is argued that digesting food waste in WWTP potentially decreased the CH_4 emissions, as opposed to it being sent to landfill (USEPA, 1999). Newer technologies are being introduced that palletize SS, with prior heat treatment, reducing pathogens and odour. While is this beneficial for public acceptance of SS, it still does not cogitate the fact that metals and organic pollutant still remain present in it and embed even more energy into the end product.

SS coming out of WWTP are up to 70-98% water, making them very heavy to transport and very energy intensive to burn. About 20% incinerated, sludge is inherently a very moist substance. A kinetic analysis of sewage sludge reported that they range between 366.58 KJ/ mol of municipal sludge and 268.46 KJ. Mol of pharmaceutical sludge (Jensen & Jepsen, 2005).

Currently 85% of the American population is connected to a sewage system, with many parts of rural America still unconnected to central sanitation systems (EPA Biosolids, 2021). As more and more people are expected to get connected to WWTPS, there is an expected increase in sludge in the near future, although it starts to taper off after mid 2030. Currently, we are producing around 8.7 (± 0.4) MMT of sewage sludge every year in the USA as a dry weight, but this weight is more when the water content is added to it. By 2050 we are estimated to produce around 10 (± 0.8) MMT. So far, we have produced around 308 (± 32) MMT of sludge in the past and are likely to produce 275 (± 30) MMT in the future, without any changes in infrastructure and treatment processes.

Given that USA is unlikely to constitute the WMH, and increate waste before landfilling, based on the value inherent in SS, we suggest a novel approach to treat SS like an asset: landfills dedicated to solely sewage sludge. This approach would be taking the Circular Economy pathway, as all valuable aspects of SS would be exploited (energy, nutrients, and metals). Many landfills already extract and use methane, with homogenous landfills dedicated to SS, WWTP could essentially save on the capital cost and infrastructure to set up methane extraction capabilities in-situ at the WWTP sites. Furthermore, if each region in the USA had its own dedicated homogenous landfill, containing SS, transport cost could be reduced substantially. The benefit in this approach is reclaiming the value from metals, as the metals with the heaviest atomic mass would aggregate at the bottom, with the increasingly lighter element aggregating toward to top. These elements could be minded by future generations. The pandemic has seen a hearty increase in mining costs, as elements found in this study have shown a 24 to 50% increase in cost per ounce. Instead, homogenous landfills could be mined for an array of metals by future generations avoiding all the current barriers to landfill mining, that stem from the risk and economic futility of mining mixed landfilled waste, where any one material is too contaminated to forage for.

2.4 Conclusions

There is an estimated 6.8 MMT of metals going to be embedded in American sewage sludge, from now until 2050. The concentrations range from 102 to 105, creating a substance of value. May regions in the USA exhibit distinct characteristics in the range of elements sequestered in SS, from the north-east had the lowest concentration of elements (<25%), closely flowed by south-west (<28%). The south-west accounted for over 60% of the distributions of Iron, Zirconium, Hafnium and Ruthenium. Ruthenium was only found in south-west and west of the USA. In comparing elements found in SS from 2001 samples, vs 2015 samples, it was found by large, rare elements (e.g, Ce, Nd, Tm, Lu) had a statistically significant increase in the year 2001 ($p < 0.05$) and precious elements were 20 times higher in concentration (mg/kg) in 2001, than in 2016. At large 2001 data were higher in concentration. Only palladium was found to be higher in 2015. Rhenium was only found in 2015. This study found a total of <$24B ± $1.6B USD (in 2021 dollars) latent value will be embedded in SS from now until 2050.

TRANSITION 2

In the previous chapter the elements sequestered in American sewage sludge were found to be valued at $24B ± $1.6B USD (in 2021 dollars) from now up to 2050. The next chapter tests for the same elements in the composition of sewage sludge from China. China has been known to be the industrial manufacturing region of the world. Manufacturing processes require a lot of water, and in this process many elements are found washed into the sewer lines. These elements are often valuable and have been mined at great economic and environmental cost. Thus, chapter 2 seeks to understand which elements are found in Chinese sewage sludge and compares the concentrations of these to the American findings in the previous chapter. 60 different elements were investigated, with the same lab methodology that was used in the previous chapter. The estimated sewage sludge forecasted to be made in China is also modelled and the total value of elements embedded in Chinese sewage sludge is assessed.

CHAPTER 3

VALUE OF PRECIOUS AND INDUSTRIAL ELEMENTS IN CHINESE SEWAGE FROM 2022 TO 2050

ABSTRACT

Research on sludge and biosolids in China have been largely characterized by studies expounding on their toxicity, highlighting chemical elements and metals that have adverse effects on human health and ecosystems, but very few studies have looked at characterizing the latent economic value of elements in sewage sludge (SS). SS production in China was calculated a function of population growth. Dry samples of sewage sludge collected in 2015 from 14 cities in China were furnaced, microwave and acid digested on hot plates in a metal free clean lab before being tested by ICP-MS. This study tested for 60 chemical elements and found the presence of 55 in sewage sludge. Some 5 precious metals organized in decreasing concentration (Ag, Pd, Au, Ru, Pt), 14 rare elements organized in decreasing concentration (Ce, La, Nd, Pr, Sm, Gd, Dy, Eu, Er, Yb, Tb, Ho, tm, Lu), and 36 common industrial elements. Industrial elements were detected in the highest concentration from 10^2 - 10^5 mg/kg. Precious and rare elements were found in the range of $^{10-4}$ and 10^1. Chinese SS has got nearly three times more valuable elements sequestered in SS than American SS samples from the same period. 12 industrial elements (Phosphorous, Zinc, Chromium, Copper, Nickel, Lead, Tin, Arsenic, Antimony, Molybdenum, Cadmium and Rhenium), and 5 precious elements (Silver, Palladium, Gold, Ruthenium, Platinum) were found enriched in Chinese SS. China is estimated to produce between 819 - 910 million metric tons (MMT) of SS between 2022 and 2050. An estimated 14.9 MMT (± 1.7) MMT of valuable elements will be sequestered in sewage sludge in the next 28 years, worth a

cumulative amount of 94 (± 20) billion USD. Given that wastewater treatment plants are expected to grow, the potential economic and ecological gains of extracting elements, especially metals from waste will become increasingly significant. In the interest to plan for and implement resource recovery using circular economy initiatives, homogenously filling select landfills with only SS would increase the ability to landfill mine these elements for future generations.

3 Introduction

Sewage sludge, a remain from wastewater treatment plants (WWTP) after treatment actives such as precipitation, coagulation, and adsorption, were typically postulated as a substance rich in nutrients such as phosphorous, nitrogen and organic carbon, often dispersed to farmers as free fertilizer before the impact of high metal concentrations in SS was detected. Farm crops/ plants take up the metals making it bioavailable to human food consumption, negatively affect human health outcomes. The permitted threshold for heavy metals in SS is 456, 43, 1099, 263 and 133 mg kg−1 for Copper, Nickel, Zinc, Chromium, and Lead, respectively (Geng et al., 2020). Between the years 2000 and 2019, most of the published reports of elemental testing of SS was for a series of five to eight metals, such as Cd, Cr, Cu, Hg, Ni and Pb, only (Fuentes et al., 2004; Fytili & Zabaniotou, 2008; Jiménez et al., 2004; Sello Likuku et al., 2013). In more recent years scientists have elected to test for more elements in the light of viewing SS as “urban mines”.

China’s population in 1990 was 1.1 billion. By 2015 it was 1.3 billion and has currently now reached its peak at 1.4 billion. By 2050, it is expected to stabilize at 1.2 billion (World Bank, 2021). Increasing industrialization, urbanization and economic growth has come with a huge environmental cost to China. In addition to solid waste, the increased production of sewage sludge (SS) has been a tremendous hazard and cost, causing a major environmental and human health challenge to China, as above 85% of it has been disposed of in environmentally un-sound ways (Meng et al., 2016).

Countries handle the end-of-life of SS in different ways. China currently incinerates and landfills roughly 50% of its SS, whereas Germany, France and Switzerland do not landfill any sludge at all, but instead choose to incinerate up to 90% of it. In a recent legislation (Inglezakis, Zorpas, Karagianides, et al., 2011), the Chinese government declared the prohibition of using SS as crop fertilizer, making the end-of-life treatment and disposal of sewage sludge an issue of national concern for the Chinese government (Feng et al., 2015). Some authors argue that incinerating of sewage sludge is not practical, as dewatering and extracting the water content to make it combustible is an energy intensive process, making the net energy gains from combustion inefficient. Others point out that landfilling SS increase methane and thus carbon emissions (Peccia & Westerhoff, 2015). Peccia et al., point out that more should be expected of SS, shifting from it as a "liability towards recovery of embedded energy and chemical assists, while continuing to protect the environment and human health." In light of this, we assess for the presence of 60 elements in sewage sludge from samples collected in 2015 from 14 cities in China.

3.1 Materials and Methods

Please note that the methodology section is the same as for above section. Dried sludge samples were obtained from 14 wastewater treatment plants from 14 cities in China from the year 2015/16. The sludge samples were dried and stored at -20 degrees Celsius as part of the Human Health Observatory sample archive located at the Center for Environmental Health Engineering at the Biodesign Institute in Tempe, Arizona, USA.

3.1.1 Materials and Reagents

The preparation, digestion and analysis of the dry SS was undertaken by the W.M Keck Foundation Laboratory for Environmental Biogeochemistry, a metal-free lab, with Ultra-Low Penetration Air (ULPA) filtered Class 10 laminar flow/exhaust workspace for ultra clean sample preparation and acid distillation, maintained at a Class 10,000 conditions for quality control and assurance, specifically designed to test trace elements. All reagents used in sample digestion or chemical purifications are trace metal grade or better. Reagents used in the preparation of the samples were trace grade or better. The water utilized in cleaning lab material and making all regents were obtained from a dedicated ultrapure 18.2 Ω water system supplied throughout the laboratory. More information in SI.

3.1.2 Sample digestion and elemental analysis

Samples were 1) ashed in ceramic crucibles at 550°C overnight to degrade organic matter and make the multi-acid digestion procedure more effective. This was followed by 2) an overnight pre-digest with nitric acid to prevent uncontrolled reactions during the microwave digest. The pre-digest was followed by 3) a microwave digestion in Mars 5 microwave system and completed by 4) repeated multi-acid hot plate digestions for maximum solubilization of solid material. 5) Samples were centrifuged to separate any small amount of residual solid, and 6) samples were then diluted for analysis by ICP-MS, in a modification of (Westerhoff et al., 2015). Hydrofluoric acid was not used, because the goals of this research were to determine the metals available for recovery in industrial processing. Although hydrofluoric acid would have improved the total metal recovery by degrading any silica tetrahedra present in mineral material, it would substantially increase the cost and hazard when scaling up any recovery processes. Details of each step are below.

Approximately 0.150 g of dried sludge sample was heated in a ceramic crucible to 550°C for 12 hours using a Thermolyne™ Tabletop Muffle Furnace (Thermo Scientific, Waltham, MA). Samples were then transferred to Teflon microwave digestion vessels with minimal amounts of 18.2 MW water to minimize sample loss. In order to prevent highly exothermic, uncontrolled reactions that could cause sample loss in the microwave, samples were "predigested" with 3 mLs of 16 M HNO_3, added in small increments while monitoring any foaming reactions. Samples were left to degas and react overnight in a laminar air-flow hood. Samples were then microwave digested using a MARS 5 with an additional 4 mL of 16 M HNO_3 and 1 ml of 12 M HCl. The microwave digestion profile is as follows: 20-minute ramp to 150°C, 15-minute ramp to 180°C, 30-minute hold at 180°C.

Post-microwave digestion, samples were transferred to Teflon digestion vessels (Savillex, USA, see details in Supplementary information), and dried in ULPA filtered air on a hot plate at 150°C in a laminar flow exhaust hood. Samples underwent hot plate digestion, alternating addition of an aqua regia acid solution (1 mL of 16 M HNO_3 and 3 mL of 12 M HCL), followed by sample drying, with a reverse aqua regia acid solution (3 mL of 16 M HNO_3 and 1 mL of 12 M HCl) followed by sample drying. This alternation of acid was repeated until there was no more solid material, or there was no decrease in the amount of material between steps.

Samples were then transferred to 15 mL metal-free centrifuge tubes (VWR tube 15 mL Metal-free, catalog #89049-170 VWR, Visalia, CA) and diluted to ~13.6 mL total volume 0.32 M HNO_3 and 0.3 HCl. Samples were centrifuged at 2000 rotations per minute (rpm) for 5 minutes, the supernatant decanted and centrifuged for an additional 10 minutes at 6000 rpm. Supernatant aliquots of 0.25 mL were transferred and diluted to 15 mL total volume with a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl. For samples requiring additional dilution steps, 0.25 mL of the final dilution was transferred and diluted to a total volume of 5 mL, in a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl for ICP-MS analysis (ThermoFisher Scientific iCAP Q, with CCT option). The addition of HCl improved the stability of some elements such as platinum group elements, which are poorly soluble in nitric acid alone.

3.1.3 Sample Processing

The laboratory building requirements of this lab also stipulated a “minimal metal” construction, with the interior parts of the lab constructed of polypropylene, and minimal expose to metal. Approximately 0.150 g of dried sludge sample was heated in a ceramic crucible to 550°C for 12 hours using a Thermolyne™ Tabletop Muffle Furnace (Thermo Scientific, Location). Samples were then microwave digested using a MARS 5 with 4 mL of 16 M HNO_3 and 1ml of 12 M HCl. The microwave digestion profile is as follows: 20-minute ramp to 150°C, 15-minute ramp to 180°C, 30-minute hold at 180°C. Post-microwave digestion, samples were transferred to Teflon digestion vessels (Savillex, USA), and dried in ULPA filtered air on a hot plate at 150°C in a laminar flow exhaust hood. Samples underwent hot plate digestion, alternating addition of acid solution (1 mL of 16 M HNO_3 and 3 mL of 12 M HCL), followed by sample drying 11 to 15 times. The process was repeated 11 to 15 additional times with 3 mL of 16 M HNO_3 and 1 mL of 12

M HCl. Samples were then transferred to 15 mL metal-free centrifuge tubes (Company, location), and diluted to ~13.6 mL total volume 0.32 M HNO_3 and 0.3 HCl. Samples were centrifuged at 2000 rotations per minute (rpm) for 5 minutes, the supernatant decanted and centrifuged for an additional 10 minutes at 6000 rpm. Supernatant aliquots of 0.25 mL were transferred and diluted to 15 mL total volume with a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl. For samples requiring additionally dilution steps, 0.25 mL of the final dilution was transferred and diluted to a total volume of 5 mL, in a final molar concentration of 0.32 M HNO_3 and 0.3 M HCl for ICP-MS analysis.

3.1.4 Inductively Coupled Plasma - Mass Spectrometry (ICP-MS)

Samples were analysed by quadrupole Inductively Coupled Plasma-Mass Spectrometry (ThermoFisher Scientific iCAP Q, with CCT option). The instrument was tested for stability and sensitivity in a variety of ways, as well as approved for oxide production ratio and doubly charged production ratio before each sample was measured. The instrument passed mass and cross calibration and daily performance reports standards, which is important to the accuracy and precision of the data. Calibration standards were made up from single element certified ICP solutions. An internal standard solution of 100 ppb Sc, Y, In, and Bi was added by a second line into all measured solutions (blanks, standards, and samples) and was used to monitor and correct for potential instrument changes over time in the form of sensitivity drift and plasma suppression. Check standards and blanks were measured every six samples. Samples were typically measured at multiple isotopes whenever possible to monitor for interferences, but only data from a single isotope are reported in the summary table. Even though the instrument could detect most isotopes of an element, the most abundant isotope, or the isotope with the lowest detection limit, was reported. For example, three masses of iron (^{54}Fe, ^{56}Fe and ^{57}Fe) were measured by the instrument. Given that the standard deviation of the concentrations measured at the three isotopes was generally less than 5%, only data from the most abundant isotope ^{56}Fe, with the lowest detection limit, are reported.

3.1.5 QA/QC

Certified standards were used for quality control. Standard Reference Material 2782 (Industrial Sludge, NIST 2782) was employed as the certified standard to verify reproducibility. Method validation was tested for accuracy and reproducibility by spiking six distinct samples with metals at similar concentrations to the sludge samples for consistency of element recoveries and including process blanks in each batch of samples. Duplicates and triplicates were also run of specific samples to test for precision. The average recovery of the certified standard was 63% with the standard deviation of 8%. The average spike recovery in fortified authentic samples was 67% +/- 19% STD. The average standard deviation for duplicates and triplicates was 14%.

3.1.6 Statistical Comparison between China and USA

All the statistical tests were performed in the R software v.4.1.1. Elements were classified into groups (precious, rare, industrial and other) based on Suanon et al., (2017) classification on chemical elements (APPENDIX A, Table 1-4). Data found in this study was compared to SS elemental analysis from sludge samples from USA tested in the same batch for the same year ($p<0.05$). Data was first assessed for normal distribution using the Shapiro-Wilk Normality test. Subsequently, a Kruskal-Wallis test was employed to look at differences in the mean concentration distributions between the two time periods ($p < 0.05$). Further analysis using a post hoc Dunn Test was done to know if there was a statistically significant difference in mean concentrations by year and by element ($p < 0.05$). Subsequently, an effect size test was conducted to understand if year alone a predictor of difference in mean concentration between the two sample locations was.

3.1.7 Enrichment Factor

Enrichment levels indicate the extent to which an element is concentrated in soil from anthropogenic sources (Barbieri, 2016; Muzerengi, 2017). The comparison of the tested element with the background concentration of the same element in soils is indicated by the Enrichment Factor. Background concentrations were obtained from World Atlas (2021). A positive value indicates the degree with each element is enriched in sludge, supporting the argument that enriched elements can potentially be extracted or mined from this matrix. An EF above 5 is considered significantly enriched (APPENDIX A, Table 5).

$$EF = \frac{(M/RE)_{SS}}{(\frac{M}{RE})_{Background}}$$

Where,

$$EF = Enrichment\ Factor$$

$$M/RE_{SS} = Concentration\ of\ Element\ in\ Sample\ (\frac{mg}{kg})$$

$$M/RE_{Background}$$

$$= Reference\ Concentration\ of\ Element\ sourced\ from\ Word\ Atlas\ (\frac{mg}{kg})$$

3.1.8 Sludge Volume Inventory

All the statistical tests were performed in the R software v.4.1.1. Population data was retrieved from the world bank (World Bank, 2021). Sludge production is estimated at 26 kg^{-1} $capita^{-1}$ year (Westerhoff et al., 2015), a Chinese sludge study estimated SS production in China to be 16 kg^{-1} $capita^{-1}$ year (Yang et al., 2015). An average was taken. The population of each year was multiplied by the sludge mass per capita per year to the get total sludge mass per year, shown by equation 1. The population forecast from the world bank included confidence intervals for confidence intervals which were also multiplied by the same factor to provide the lower and upper bounds of SS.

Equation 4.

$$P_n * \left(\frac{K_n}{1000}\right) = SS_n$$

Where,

$$P_n = Population\ at\ n\ year$$

$$K_n = Sewage\ sludge\ (kg)\ per\ capita\ at\ n\ year$$

$$SS_n = Sewage\ Sludge\ (metric\ t) at\ n\ year$$

3.1.9 Element Inventory

All the calculations were performed in the R software v.4.1.1. Having established the concentration of elements, the metric tonnage of elements sequestered in sludge in the past and in the future was calculated using equation 2.

Equation 5.

$$\sum_{i=1}^{n} M = SS_n * (\frac{C}{1000})$$

$$M = Mass\ of\ Element\ at\ n\ year\ (in\ metric\ t)$$

$$SS_n = Sewage\ Sludge\ (metric\ t)\ at\ n\ year$$

$$C = Concentration\ of\ element\ (kg^{-1}t)$$

$$i = Time\ (in\ years, 2022 - 2050)$$

3.1.10 Economic Value Analysis

The value of the elements was collected from various sources (Westerhoff et al., 2015) and using the equation 3.

Equation 6.

$$ZT = M_t * Z$$

Where,

$$M_t = Mass\ of\ element\ from\ 2022 - 2050\ (metric\ t^{-1}year)$$

$$Z = Price\ of\ element\ in\ (USD/t)$$

$$ZT = Total\ values\ in\ USD\ of\ that\ element\ accumilated\ from\ (2022 - 2050\ in\ USD)$$

3.2 Results

3.2.1 Concentration Hierarchy and Geospatial Distribution

Iron, Aluminium, Calcium, Phosphorus were found in the highest concentrations at values between 10^3 to 10^5. Figure 6 depicts the highest of concentrations were industrial elements, with precious and rare elements in the range of 10^{-4} to 10^1. Precious elements such as Silver, Gold, Palladium, Ruthenium and Platinum are in the concentration range of 10^{-3} and 10^1. The elements with the most standard deviation were Chromium, Zirconium, Tungsten and Hafnium. The elements with the least standard deviation were Vanadium, Cerium, Holmium, Gold, and Silver. In total 56 elements were found in sewage sludge, from the 60 tested. Phosphorus ranked third in concentration, after Iron, Aluminium and Calcium.

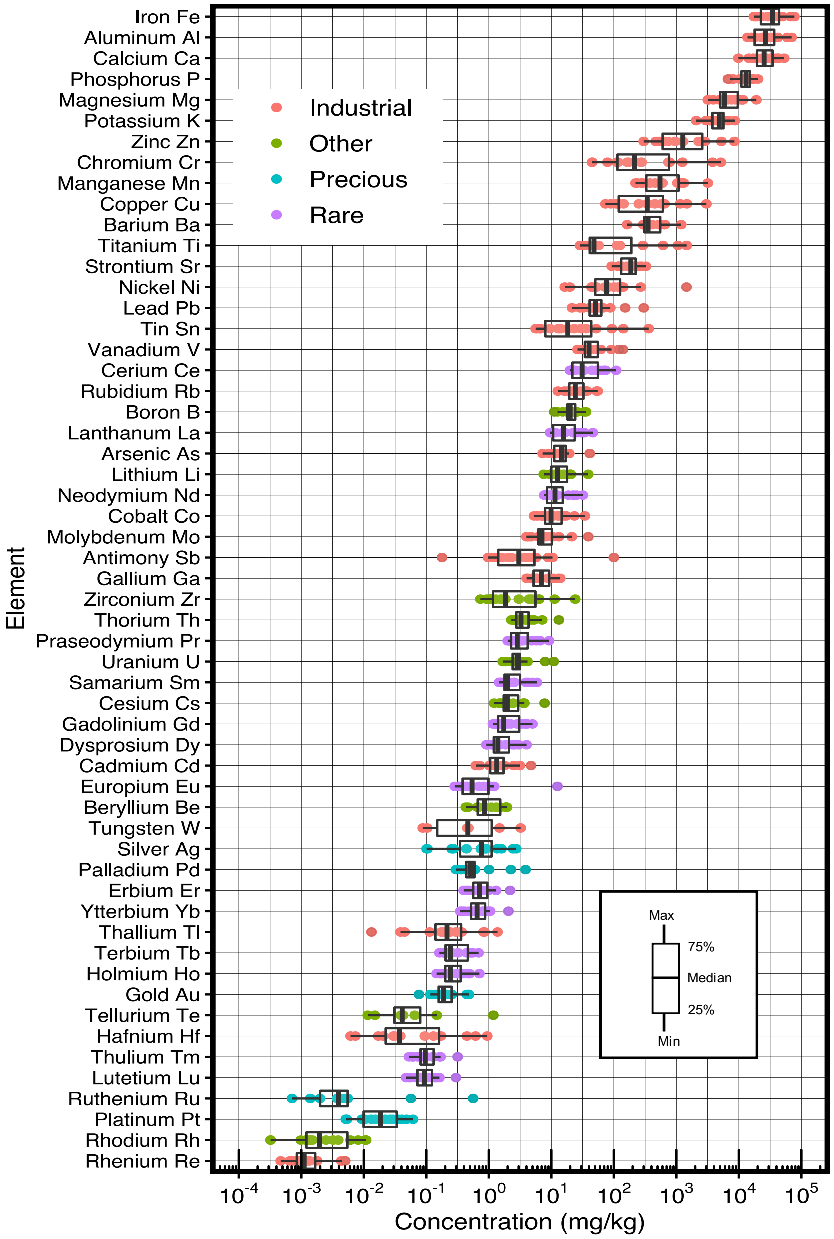

Figure 7. Box-Whisker rank order plot, organized by mean concentration of elements found in China sewage sludge samples, collected in 2015/16, as determined by ICP-MS dry weight. Whiskers are indicative of range and the box is indicative of highest and lowest quartile. Elements organized by decreasing mean concentration, while solid black line inside boxplots is indicative of median concentration. Multiple sludge samples collected from 14 wastewater treatment plants from 14 cities in the China in 2015/16. The sludge samples were dried and kept frozen at -110 degrees before being thawed, acid digested and tested by Inductively Coupled Plasma - Mass Spectrometry.

3.2.2 Comparing USA vs. China Elemental Concentration

Both American and Chinese sewage sludge were tested, with no variation in the methodology of the lab work, thus, it was advantageous to see if Chinese sewage sludge were statistically significantly different from American sewage sludge (figure 7). The normality of the datasets was determined using Shapiro-Wilk test for normality test, which showed that the data was non-parametric. Subsequently a Kruskal-Wallis test (a T test for non-parametric data) looked the differences in the mean concentration distributions between the two locations and found that there were statistically significant differences for elemental concentration by location ($p <$ than 0.05) (See Appendix 1). Further analysis was done using a post hoc Dunn Test was done to know if there was a statistically significant difference in mean concentrations by location and by element for 34 of the 56 elements. The Dunn test revealed that over 60% of the samples did show statistically significant differences in their distributions ($p <$ than 0.05). Subsequently, an effect size test indicated that only 6% of the variation in mean concentrations could be explained by the sample year (See Appendix A). This meant that while 60% of the samples did show a small difference in mean distribution by year, the year on its own cannot account for these differences. Figure 7, panel B shows that most of the elements from 1 (e.g., Palladium, Barium, Zirconium) 15 times greater (e.g., Chromium) in concentration in China than in the USA. Rare, other, and industrial elements showed the most statistical difference between USA and China ($p <$ than 0.05), with other and rare being 1.5 and 2.4 times greater in China.

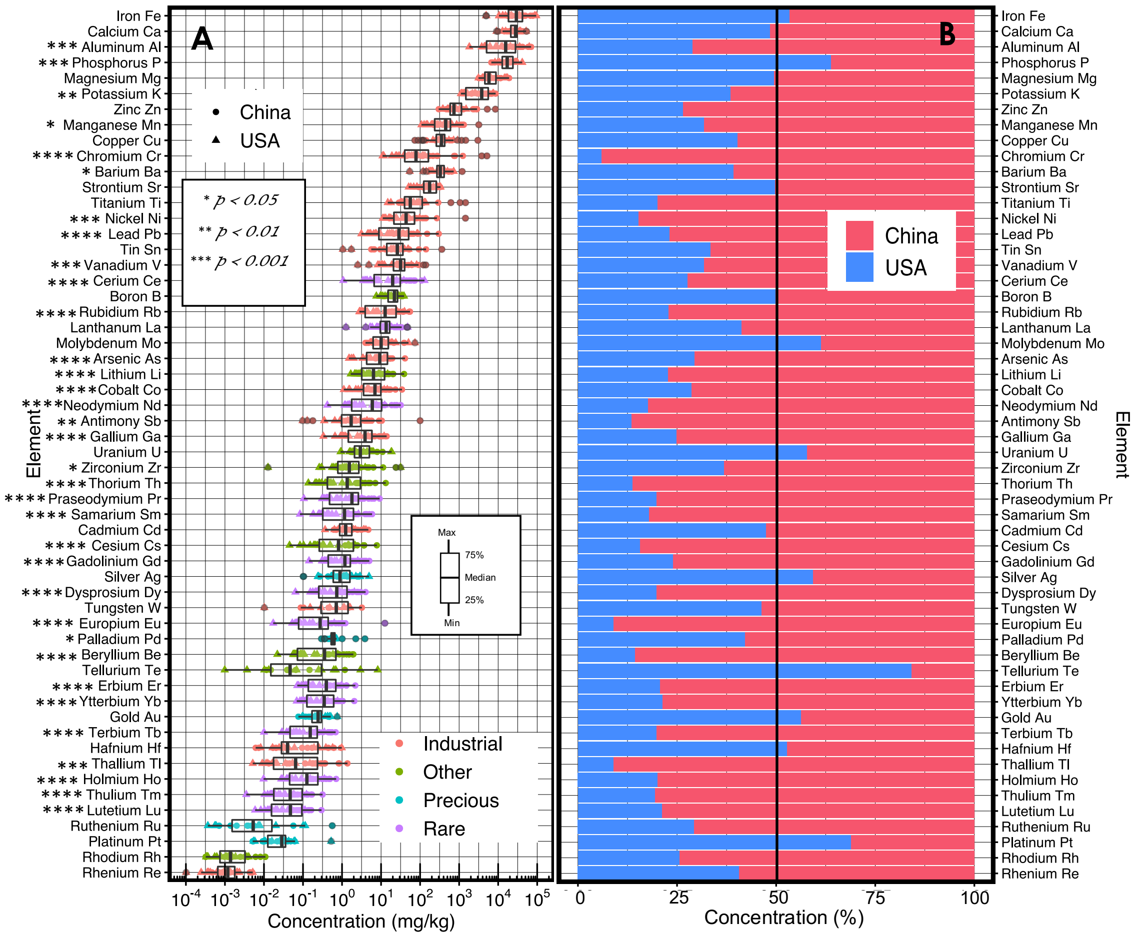

Figure 8. Comparing elemental distribution between China and USA. A Rank order of the abundance of the different elements from dry sewage sludge collected in China in 2015/16 (circle) and from USA (triangles) and as determined by ICP-MS dry weight. Elements organized by decreasing total mean concentration, while solid black line inside boxplots is indicative of median concentration. B Percentage distribution of each element between China (pink) and USA (blue).

3.2.3 Enrichment Factor China

The range of elements found in Figures 7 and 8 indicate the elements present in sewage sludge, but they do not indicate how much these elements are enriched in sewage sludge. Enrichment levels indicate the extent to which an element is concentrated in soil from anthropogenic sources (Barbieri, 2016). The comparison of the tested element with the background concentration of the same element in soils is indicated by the

Geoaccumilation Index. A positive value indicates the degree with each element is enriched in sludge, supporting the argument that enriched elements can potentially be extracted or mined from this matrix. A GI above 4 is considered highly enriched. Tellurium, Gold, Antimony, Ruthenium, Palladium and Tin are all highly enriched, and are predominantly industrial and precious elements. It is indicative that these elements stem from anthropogenic sources. Twenty elements were enriched in Chinese sludge, compared to only fifteen in American SS. Rare elements are not enriched in sewage sludge (Figure 9).

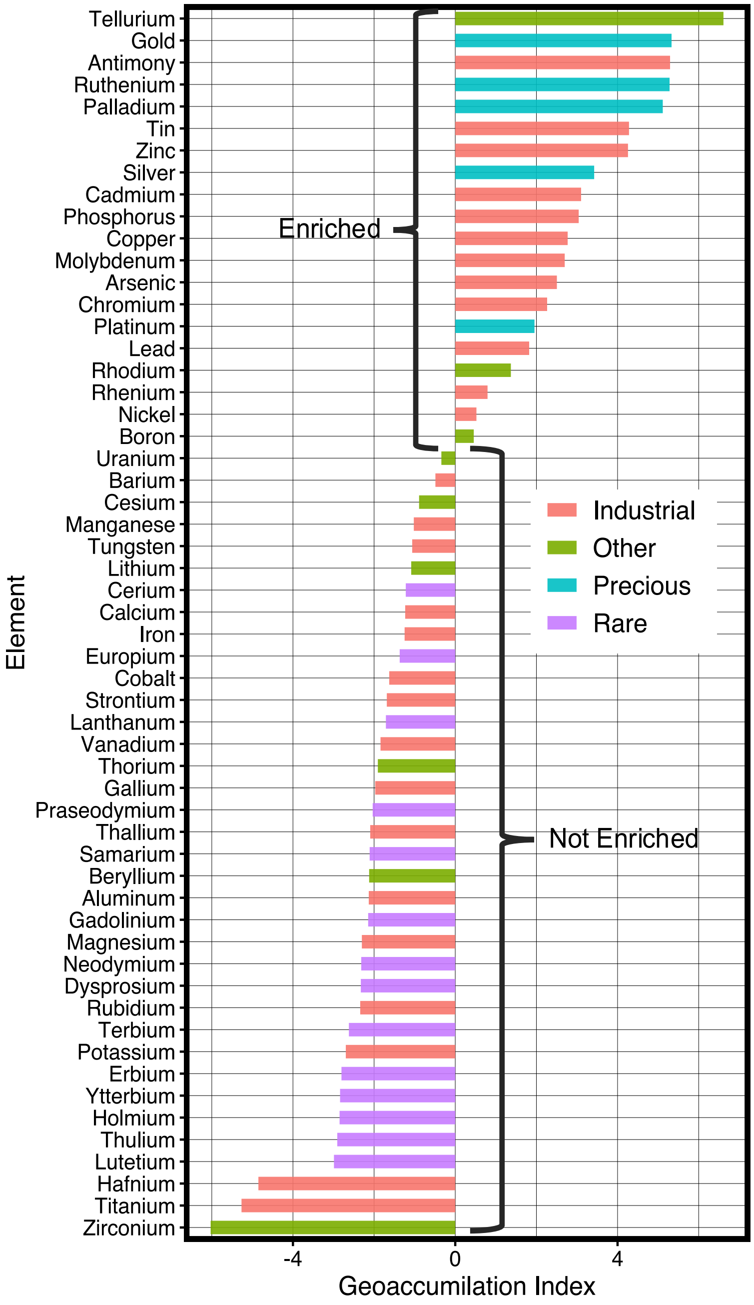

Figure 9. Elements enriched in Chinese sewage sludge, indicating presence from anthropogenic sources. 12 industrial elements and 5 precious elements were enriched in sludge, indicative of mining potential relative to background concentrations. 36 elements minimally enriched in sewage sludge.

3.2.4 Inventory of Sewage Sludge Mass for China till 2050

Sludge prediction follows the Chinese population curve, with the steep rise in population from 1990 to mid 2030. This is reflected in sludge production going from 24 MMT in 1990 to 30 MMT in 2022. The highest estimated sludge amount per year is 32 MMT with the lowest going back to 26 MMT per year.

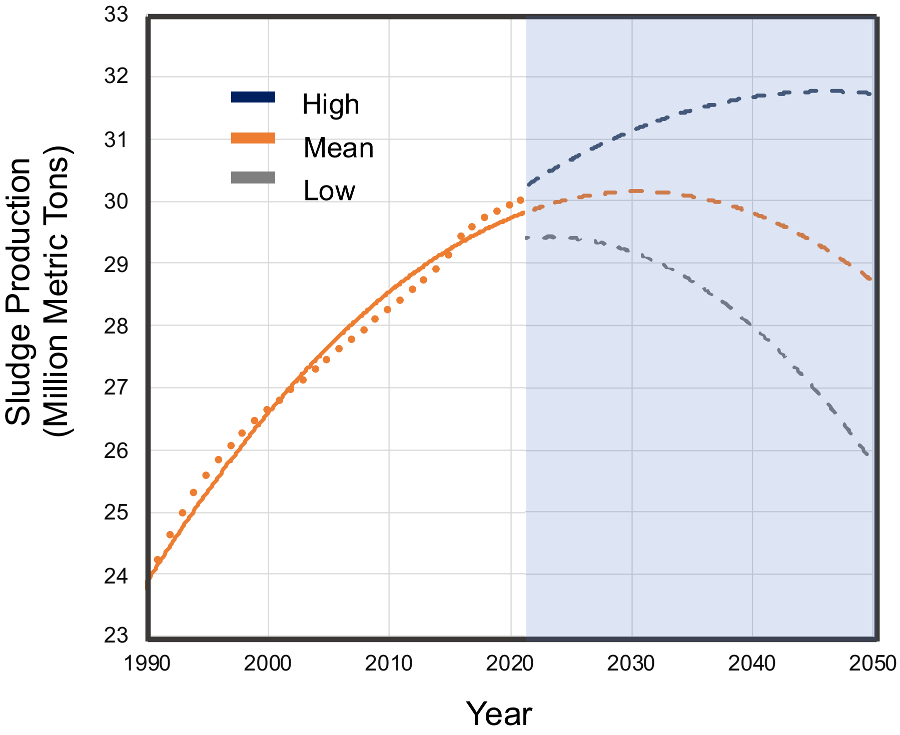

Figure 10. Predicting amount of sewage sludge (dry weight) in the China from 1990 to 2050. Navy and grey line indicate high and low estimates, with Orange line indicative of mean predicated tonnage by year. All estimates based on 18 kg-1 year. Shaded region is the future trend line extrapolated to 2050. Calculation based on World Bank US population predications.

3.2.5 Latent Mass of Valuable Elements in Sewage Sludge in China

A total of twenty elements are highly accumulated in sewage sludge from now until 2050. Twelve industrial elements and five are precious elements. Phosphorous is expected to accumulate at the highest mass with 1.6×10^7 ($\pm 7.05 \times 10^5$) MT, closely followed by Zinc and Chromium at a mass between $1.7\text{x}10^6$ (± $3.6\text{x}10^5$) – $6.5\text{x}10^5$ (± $2.5\text{x}10^5$) MT (figure 10, panel A). Rhenium and Rhodium have the lowest mass aggregations over 28 years at 1.6 (±$2.7\text{x}10^{-1}$) MT and 3.46 (±$6.8\text{x}10^{-1}$) MT. The price per ton of Phosphorus, Zinc and Copper is 388, 4475 and 6181 USD^{-1} t respectively, accruing 4,504 million 8,037 million and 5,027 million USD in value in 28 years. Cadmium, Antimony, Arsenic, Rhenium and Boron are the only elements that accrue a cumulative value between 2.6 million and 139 million USD. Gold and Silver accrue a cumulative mass of 215.04 (±22.8) and 1079 (±192.3) MT, which amount to a cumulative dollar value of 1,045 (±18.6) million USD and 13,714 (±145) million USD, respectively (figure 10, panel B). In total, 14 (±1.7) million MT of mass of elements, worth an estimated 94 (±20) billion USD will be sequestered in sewage sludge from now till 2050 in China (figure 10).

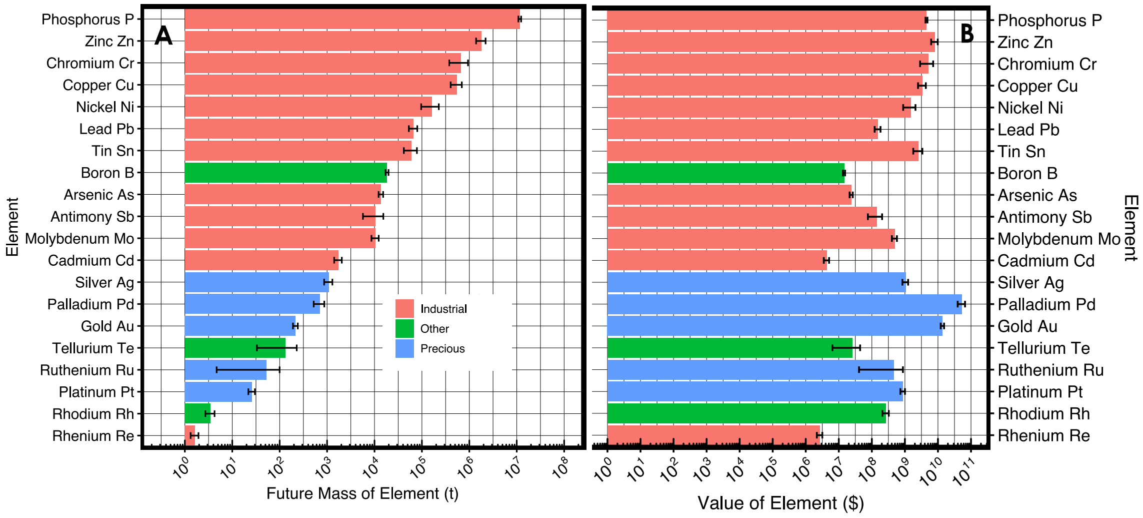

Figure 11. Mass select Elements and latent value of element accumulated in Chinese sewage sludge from 2022-2050, based on samples collected in 2015. A Mass of each element accumulated in sewage sludge in 28 years in China. B Latent cumulative value in USD of all elements in sewage sludge in 28 years. 20 elements

3.3 Discussion

Two prior studies look at SS as in-depth as this study from Chinese Sewage Sludge. Yang et al., (2014) analysed SS samples collected in 2006 from 107 municipal WWTP located in 48 cities in China. Nevertheless, they only tested for 9 elements, mainly heavy metals. Their reported values for As, Cd, Cr, Cu, Ni, Pb and Zn were 20.2, 1.97, 93.1, 218.8, 48.7, 72.3, 1058 mg^{-1} kg. They also found Hg at the concentration of 2.13 mg^{-1} kg. This study found concentrations of the same elements to be As= 15.3, Cd=1.93, Cr=735, Cu=614.20, Ni= 180.93, Pb=74, Zn=2008 mg^{-1} kg. In our study Hg was not enriched. Arsenic saw a 5mg/kg increase since 2006. Cr, Cu and Zn, saw a significant jump. Only Ni saw a decrease. Suanon et al conducted a study of 56 elements for three WWTPs in China. Although Suanon et al., (2017) collected sludge sampled from only three WWTP, they have much more information of the conditions and treatment that their samples were collect in. For example, they note that one of their samples was subject to screening, grit chambers, biological treatment and aerated filter followed by UV disinfection, while the other sample was subject to a hydrolysing pond, and anoxic reactor treatment. In our study we had no information on the treatment of our samples. In all other ways, their study was very comparable to this study because they used the same protocol established by Westerhoff et al. Re was below detection limit, while in ours Re was detected at concentrations of 0.0018mg/kg in 2015 and was detected at a concentration level of 0.00 mg/ kg in 2001. In their results, Zn was enriched in 2 of the 3 plants, with W, Sn, Cd, Pd, Ag, Au, Ru, Pt, and Tb enriched in all plants. This overlaps with ours to the extent that we also saw, Au and Ag, Zn, Pt, Pd, Sn, Cd, Ru, enriched in this study. We did not see Wand Tb enriched, as they did. W is used as electrodes, in filament light bulbs and cathode ray tubes. Tb is rare and expensive and used in semiconductor devices as well as in televisions. In general, the last 30 years have seen China be the fabrication plants of much of the world's electronics and thus, it explains the enrichment of more metals in their sewage sludge. Up to 85% of Chinese sewage sludge was improperly disposed of. This study found a total of 94.9 billion USD of latent value will be embedded in SS in China from now until 2050.

3.4 Conclusion

There is an estimated 14.9 MMT of metals going to be embedded in Chinese sewage sludge, from now until 2050. The concentrations range from 10^{-4} to 10^{5}, creating a substance of value. In total 56 elements were found in sewage sludge, from the 60 tested. Phosphorus ranked third in concentration, after Iron, Aluminium and Calcium. When comparing American SS to Chinese SS elemental concentrations up to 60% of the samples did show statistically significant differences in their distributions ($p <$ than 0.05). Most of the elements were from 1 (e.g., Palladium, Barium, Zirconium) to 15 times greater (e.g., Chromium) in concentration in China than in the USA. Rare, other, and industrial elements showed the most statistical difference between USA and China ($p <$ than 0.05), with other and rare being 1.5 and 2.4 times greater in China. Twenty elements were enriched in Chinese sludge, compared to only fifteen in American SS. This study found a total of 94.9 billion USD of latent value will be embedded in SS in China from now until 2050.

TRANSITION 3

In the past chapters, sewage sludge, the solid by product of liquid wastewater treatment was assessed for the latent value if holds, in the form of various elements sequestered in it. Another type of solid waste is plastics. Plastics are the by-product of petroleum refining. In recent years there has been a lot of press about the repercussions of improper end-of-life management of plastics affecting the environment, wildlife, and human health. Plastics are now ubiquitous to modern life, but the improper waste management of them has adulterated many natural systems (Browne et al., 2011). A study by Geyer et al., (2015) found that 8,300 million metric tons of plastic have been made since the inception of plastics only 9% of all plastics ever made were recycled. The next chapter was based on asking, how much of all plastics ever made belongs to which companies. Fast moving consumer goods are a subset of companies that are typically low cost, high consumer demand and a short shelf life, usually packaged in paper, plastics, or metal. They are used every day and are found grocery stores all over the world. A hallmark example of an FMCG are beverage companies such as Coca-Cola, PepsiCo, and Nestlé, who use plastics to package their beverages. While the role of government, countries and consumers are explicitly highlighted in literature, very few studies discuss the role of industry in tackling macroplastics in any actionable manner. In the past decade well-known companies have made numerous commitments to reducing their contribution to plastic pollution globally, but without reported baseline values, increases, and decreases in recycling cannot be measured reliably. Thus, the next chapter assess how much plastic waste was made by three global multinational beverage companies (Coca-Cola, PepsiCo, and Nestlé), which countries their plastic waste ended up in and which ultimate end-of-life fate their plastics had.

CHAPTER 4

MASS AND FATE OF PLASTIC WASTE DISPERSED GLOBALLY TO LAND AND SEA BY TOP THREE MAJOR MULTINATIONAL BEVERAGE CORPORATIONS

ABSTRACT

Fast-moving consumer goods (FMCG) companies predominantly utilize single-use plastics in the form of polyethylene terephthalate (PET) and polypropylene (PP), which jointly account for 63% of the plastic dispersed into the global environment since the year 2000. These polymers also dominate oceanic litter and microplastic pollution. We computed the plastic mass the top three FMCG beverage companies (Coca-Cola, PespiCo and Nestlé) have produced since the year 2000: 126 ± 8.7 million metric tons (MMT) of plastic, of which 15.6 ± 1.3 MMT (12%) were projected to have turned into aquatic pollution, creating estimated externalities of $13.6B USD annually. Some 58 ± 5 MMT (46%) were estimated to result in terrestrial plastic pollution, with only minor amounts (9.9 ± 0.7 MMT, equivalent to 8%) deemed actually recycled. For each dollar of revenue, the three FMCG companies were calculated to have generated approximately 40 grams of plastic, of which 58% ± 8.9% subsequently was destined to become aquatic and terrestrial pollution. Absent of change, the three companies by 2050 will add an additional 330 ± 15 MMT plastic mass to countries around the world, costing an estimated $8 ± 0.4 trillion USD in total. While the global plastic pollution often is portraited as a wicked problem that only countries and consumers as individuals can solve, the present analysis suggests that a small subset of FMCG companies are well positioned to change the current trajectory of global plastic pollution and ocean plastic littering.

4 Introduction

Every major ecosystem has been impacted by the ubiquity of manmade, nonbiodegradable polymers. Microplastics have been found in the depths of ocean trenches and the tissues of animals and humans (Halden et al., 2010; Cook & Halden, 2020; Morét-Ferguson et al., 2010; Pabortsava & Lampitt, 2020). Precursors to microplastics are mismanaged microplastic consumer goods, particularly those having a documented history of leakage into the environment, such as plastic beverage containers. The global inventory of synthetic plastics ever produced was estimated to have reached 8,300 million metric tons (MMT) by 2015 (Geyer et al., 2017). The majority of that mass (56%) was created from the year 2000 onwards, with continuing growth being projected absent of significant corporate or regulatory change.

Among the many different uses of plastic, packaging is the single largest market (Geyer et al., 2017; Plastics Europe, 2018); some 40% of plastic waste generated in the past two decades was derived from packaging, amounting to 1,818 MMT (Geyer et al., 2017). Packaging waste has the shortest product lifetime ranging from as short as 15 minutes to 6 months, with post-consumption environmental half-lives measured in decades, centuries or even millennia (Plastic Oceans, 2021; Geyer et al., 2017). The proliferation of single-use containers and the number of products of fast-moving consumer goods companies (FMCG) utilizing plastics has nearly doubled in the last decade (Krause, 2021; Tan et al., 2021). Single-use plastics are projected to reach 48 MT per annum in 2025, with an annual growth rate of 4% (Chen et al., 2021; Deloitte, 2020; Joseph E. Johnson, 2020; Krause, 2021; Tan et al., 2021). Some 42% of all non-fiber plastics which have been used for packaging are predominately composed of polyethylene terephthalate

(PET) and polypropylene (PP). The single largest contributors to the plastic waste problem are PET and PP, accounting for 402 MMT and 718 MMT, respectively, or 63% of all plastics dispersed in the environment since the year 2000 again predominantly from FMCG products. The latter are non-durable products that sell rapidly (Kenton., 2021; Kerry et al., 2008). Hallmarks of FMCG are low cost, high consumer demand, and a short shelf-life. Important FMCG include food products, drinks, over the counter drugs, and cosmetic products. Most people globally use FMCG every day, and they account for more than half of all consumer spending (Kenton., 2021). This is problematic because plastics from packing have a short useful lifespan but dominate municipal plastic waste and mismanaged plastics released into the global environment (Lebreton et al., 2019). It is no coincidence that the most prevalent plastic pollution found in oceans are PET and PP, which also dominate the plastic packaging FMCG market (Gewert et al., 2015; Ioakeimidis et al., 2016; Schwarz et al., 2019; Wagner et al., 2017).

Beverage companies selling soft drinks and bottled water since the 1990s have moved from glass to plastic packaging made from PET and PP to simplify their material flow while also increasing their bottom line (Gerassimidou et al., 2022; Gomes et al., 2019; Pasqualino et al., 2011). For example, the distribution portfolio of packaging by the Coca-Cola company today is 44% PET (the highest), compared to 24% for aluminium and steel, and 9% for glass (Coca-Cola, 2022). While the soft drink industry has seen decreases in sales over the years, the rise in bottled water and bottled carbonated non-sugary beverages is one of the biggest contributors to the rise in use of PET and PP. These products are packaged in plastic bottles because they are lighter to transport through the global supply chain than metal or glass, they are cheaper to manufacture, and plastic from petroleum is more easily sourced globally than are alternative materials subject to recycling and reuse such as aluminium, steel and glass. North American consumers average 108 litres of carbonated drinks per person (Health Food America, 2018). Bottled water accounted for roughly 24% of the beverage consumption in the USA, closely followed by carbonated soft drinks at 18% (International Bottled Water Association, 2020). In many regions of the world, bottled water is the only perceived source of clean water constitutes an FMCG of high demand. The per-capita consumption of bottled water in the USA in 1999 was 61 litres (16.2 gallons) and 159 litres (45.2 gallons) in 2020 (IBWA, 2021). The water bottling industry's revenue was $6.64 billion USD in 2022 and the market is expected to grow annually by 9.81% (CAGR 2022- 2026; Statista, 2022). Both in North America and East Asia the demand for bottled water is exceptionally high (Hu et al., 2011; Statista, 2022), although consumption of tap water in the U.S. is mostly safe but more risky in some seasons and regions in East Asia.

While the role of government, countries and consumers are explicitly highlighted in literature, very few studies discuss the role of industry in tackling macroplastics in any actionable manner (Barnes et al., 2009; Cole et al., 2011). In the past decade well-known companies have made numerous commitments to reducing their contribution to plastic pollution globally, but without reported baseline values, increases, and decreases in recycling cannot be measured reliably. Whereas the beverage industry is a key player in the demand, use, and proliferation of plastic products, rigorous estimates are lacking as to the amount of plastics this market sector utilizes and has dispersed into the global environment over the past two decades. Among the 32 leading beverage brands, we used available data for the three leading companies, Cola-Cola, PepsiCo, and Nestlé, that have a combined market share of 85% of the beverage industry (, and here present the first mass estimates of plastics use over the last two decades and projected out to the year 2050. Secondly, we traced the flows of plastic waste from each of these companies to destination countries worldwide, classified by region and income level (High Income = HI, Upper Middle Income = UMI, Lower Middle Income= LMI, Low Income= LI). Lastly, we traced the flows of plastic waste generated by these three companies to their final end-of-life sinks in land and sea. This paper only looks at a business-as-usual scenario and serves as an estimate for the amount of plastics that these companies have and will continue to produce absent of any changes to their business and revenue model. The overall objective of the present work was to demystify and inform the formulation of solutions to the plastic pollution conundrum that often is presented as a wicked problem not easily solvable with conventional interventions of smarter design, responsible business practices, and governmental policy interventions.

4.1 Methodology

4.1.1 Data Sources

Self-reported data on annual consumption of plastics by each individual company (Coca-Cola, PepsiCo and Nestlé) were taken from the public domain (See APPENDIX B, Table 7) for the years 2018 and 2019 (Ellen MacArthur Foundation, 2019). Data necessary to correlate plastic consumption (See APPENDIX B, Figure 1) to socio-economic status of world regions were obtained for 5 independent variables on a year-by-year basis for the duration from 2000 to 2021 from the World Bank and OECD sources: 1) Gross domestic product (GDP) (present-day $USD), 2) GNI/ capita (current $US), 3) total plastic polymer trends (MMT/year), 4) total company revenue (current $USD), and 5) waste generation rate (MMT/year), to predict the dependent variable of interest: total plastic polymer tonnage for three companies; Coca-Cola, PepsiCo, Nestlé for the same years (See Appendix B, Figure 2). After validating a positive linear relationship between the four of the five variables above and company review, the data sets were linearly fitted to obtain estimates of year-by-year plastic use for each company for years for missing self-reported data over two decades (2000 to 2021). Based on future predictions by the OECD and World Bank total world polymer mass and world gross domestic product (GDP), we also computed anticipated values of plastic waste production for future years through 2050 for these three companies by extrapolating from established relationships of past - and present-day predictors and actual data. (See Appendix B, Figure 2).

4.1.2 Localization of Plastic Waste Generation by Product Manufacturer

Global soft drink sales, in millions of liters, by geographical region for the years 2012 and 2017 were collected (See Appendix B, Equation 2). These data were converted to an average sales percentage for each of the seven regions of the world (ordered by decreasing population: East Asia Pacific, South Asia, Sub-Saharan Africa, Latin America & Caribbean, European Union, Middle East and North Africa, North America). Since Coca-Cola and PepsiCo are largely soft drink-based companies, this data was used as a proxy for their sales in those geographical regions. For Nestlé sales distribution data by region was retrieved from the company website as a percentage of sales revenue for the year 2020 (see APPENDIX B, Table 7). Gathered sales percentages were multiplied with the mass in MMT for each company's plastic waste data to arrive at the mass of plastics in MMT deposited in each of the seven regions of the world (See Appendix B, Equation

2, Table 12). To obtain the percentage of sales by income classification (HI = high income country, UMI = upper Middle-income country, LMI = lower middle-Income country, LI = low-income country) sales data by region were weighted by the population for each of the four income classifications. (See Appendix B, Table 9).

4.1.3 Analysis of End-of-Life Fate of Plastics Embedded in Company Products

To estimate the fate of plastic in any one country, data from the World Bank (See APPENDIX B, Table 7) was used (Kaza et al., 2018). To estimate the final destination of post-consumer plastics from beverage company products, the percentage of plastic waste distributed to different final sinks for each country was applied to the estimated plastic mass by company per country (Section 4.2.2). End-of-life sinks were classified into six end of life classifications; *recycling, incineration, sanitary landfill, dumping in non-sanitary landfills* (denoted by Dumped NSLF*), *mismanaged* (as defined by the World Bank) and *marine pollution* (denoted by Marine P*). The supplementary information on *marine pollution* by Jambeck et al., (2015) was summarized by income level and region to calculate the percentage of waste going to marine sources. The end-of-life waste management data were averaged by income classification and then weighted by the population of the seven world regions to arrive at the percentage for end-of-life sink for each of the seven world regions, i.e., the fraction of the total mass of plastics made by each company in units of percent (APPENDIX B, Equation 4).

4.1.4 Number of Fast-Moving Consumer Goods

The top 100 wealthiest companies, as defined by their market value, was downloaded from the Forbes website (Forbes, 2021). Each company was categorized as one of the seven categories (FMCG, Tech, Tech Goods, Oil and Gas, Biotech, Financial, Media and Other).

4.1.5 Economic Burden & Marine Clean-up Cost to the Public from Product External Costs

Taxpayer costs was calculated from supplementary information by Borrelle et al., (2020), where they state that the average global cost of collection of plastic is 156.5 USD/t on plastic waste. The average cost of sorting plastic was 142.25$/ t of plastic waste. This cost was averaged and multiplied by the total mass calculated by the above data set (See APPENDIX B, Equation 5). The cost of cleaning up just the plastic into Marine Environments by Nestle, PepsiCo and Coca-Cola was estimated using Beaumont et al., (2019) analysis on cost of marine clean-up of plastics (between 3300 and 33,000 USD/ t of marine plastic) and multiplying that by the calculated mass in this study (see APPENDIX B, Equation 7).

4.1.6 Data Visualization.

All calculation is defined in APPENDIX B, and data visualizations were performed in the R software v.4.1.1.

4.2 Results and Discussion

Four of the five variables examined as potential predictors of plastic production, GDP (0.92), GNI (0.97 value), and total plastics (0.86 value) yielded strong relations ships and thus were chosen to inform past and future year estimates (See APPENDIX B, Figure 1). Waste generation was not included in the model because it did not indicate a strong relationship with company revenue. Model results indicate the lowest overall world production of plastic from three companies was in the year 2000 at 2.6 MMT and the highest in 2011 at 8.1 MMT. The combined total mass of plastic waste generated by the three major beverage companies studied here is expected to be in the range of 14 or 16 MMT per year for the time period 2022 - 2050 (Figure13) if trends of current consumption and waste management continue unabated.

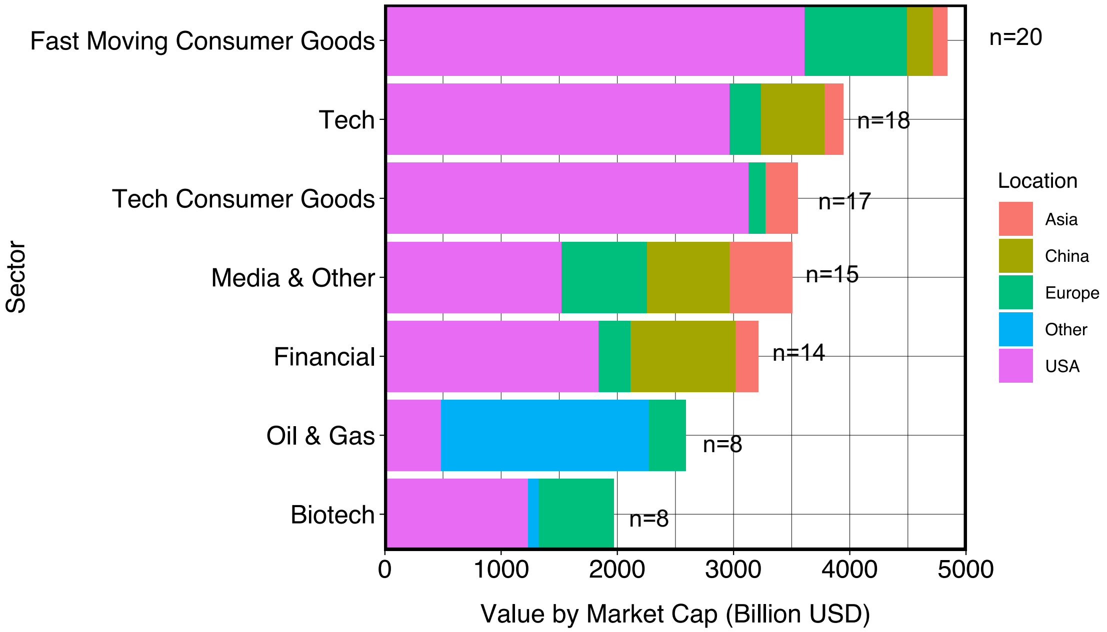

Figure 12. The Forbes list of 100 wealthiest companies aggregated by sector.

In figure 12 it is evident that FMCG have the greatest number of companies and the highest total accumulative market value, and the greatest number of companies (n=20).

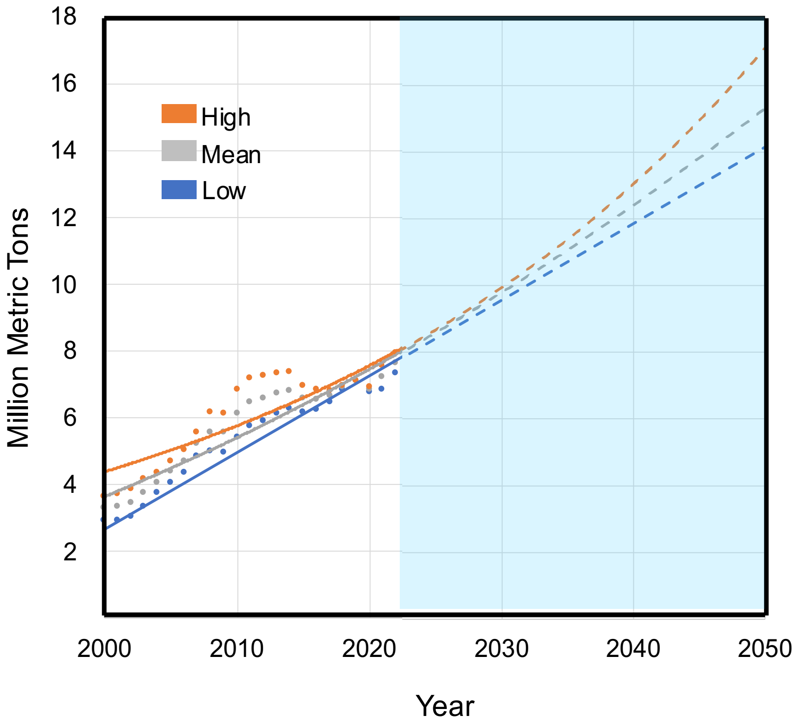

Figure 13.Mass of plastic in million metric tons (MMT) produced by three major beverage companies, representing 85% of the global beverage market, from year 2000 to 2050. The historic part of the model (2000-2021) is a function of 1) revenue from all three companies, 2) plastic polymer trends, 3) GDP and 4) GNI. The forecast (2022-2050) is a function of plastic polymer trends and GDP. [High] The highest estimates of plastic waste produced by these three companies. [Mean] The average estimate of plastic waste production. [Low] The lowest estimate of plastic waste production. The cumulative sum area under the curve for the average estimated mass of plastics (grey middle line) made by three top beverage companies over the course of 21 years is 126 MMT, (signifying 100% of total plastic mass), with the total upper estimate being 147 MMT, and the total lower estimate being 112 MMT. The grey shaded area indicates the future, from 2022-2050.

Coca-Cola, PepsiCo, and Nestlé produced a cumulative average of 54.2 ± 4.7 MMT, 42.3 ± 3.6 MMT, and 30.2 ± 2.6 MMT of plastic waste, respectively, from 2000 to the present (Figure 14). On the whole the majority of plastics gets sold to high-income (HI) countries and the least to low-income (LI) countries. Coca-Cola sells mostly to UMI countries (22.8 ± 2 MMT), while PepsiCo sells mostly to HI countries (31.1 ± 2.7 MMT), and Nestlé is split nearly evenly between the two (10 ± 2 MMT for HI and 8 ± 0.7 MMT for UMI), respectively (Fig 2). All companies combined, 78 ± 6.9 MMT, or nearly 62% of the plastic waste made between 2000 and 2022 was either disposed of in sanitary or non-sanitary landfills. At 15 ± 1.3MMT, more waste ended up in ocean sinks than was recycled (9 ± 0.8 MMT) or incinerated (10 ± 0.8 MMT).

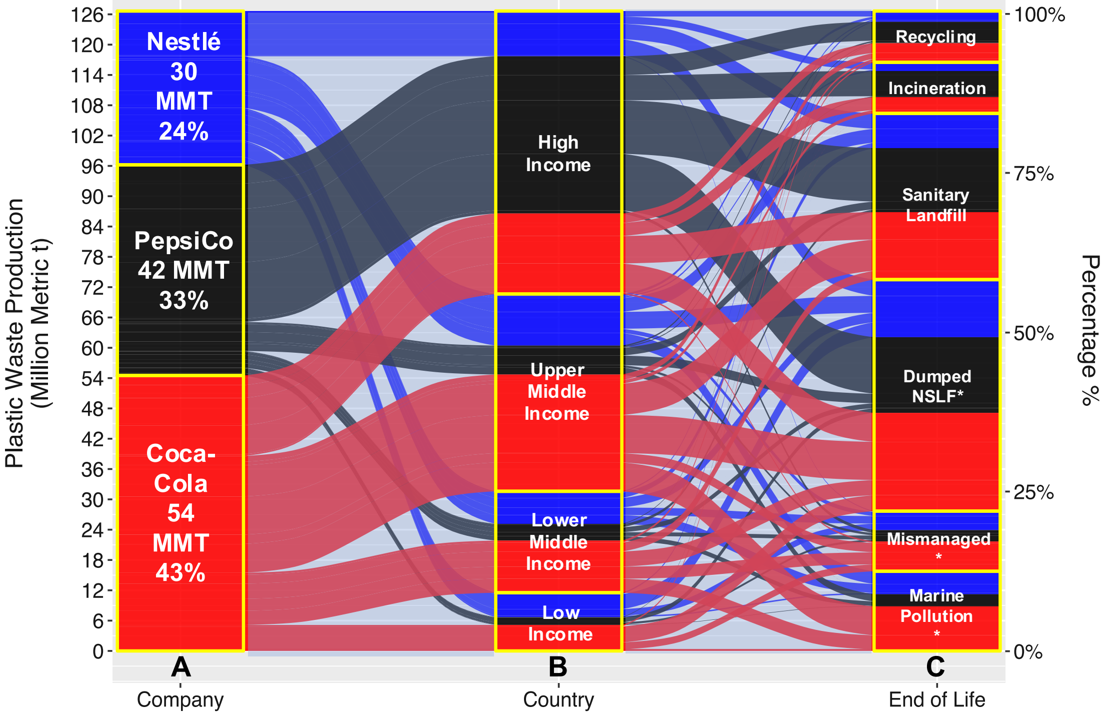

Figure 14. Sankey diagram of global flows of total cumulative estimated mass of plastics (in units of MMT) from the top three global beverage companies from 2000 – 2021 flowing to countries and then to end-of-life sinks. A-C, Mass flows from companies (organized by decreasing plastic waste mass), to countries (categorized by income classification and organized by decreasing population and) to waste end-of-life sinks (organized by increasing environmentally sound metric). Coca-Cola, PepsiCo, and Nestlé produced an estimated 54 MMT, 42 MMT and 30 MMT of plastic waste respectively, over the last two decades. (A) The sum of each horizontal bar is the cumulative sum of the average estimated mass of plastics made by three top beverage companies over the course of 21 years at 126 MMT (signifying 100% of total plastic mass), with the total upper estimate being 147 MMT, and the total lower estimate being 112 MMT. (B) Plastic migration from production point into countries where the products are sold. Economies of countries (n=185) were classified to four

income level as defined by the World Bank. Percentage of population housed by each income classification is LIC=9%, HIC=17%, UMI=33%, LMI=41%. Mean percentage of sales from companies to country grouped by income classifications is LI=10%, HI=44%, UMI=30%, LMI=16%. (C) The flows of plastic into six designated end-of-life sink as classified by the World Bank on waste sinks by country (n=185 countries). Percentage of total plastic mass to each respective sink in decreasing order is Dumped NSLF= 35%, S Landfill*= 26%, Marine P*= 13%, Mismanaged* =9%, Incineration* and Recycling* both at 8%.

Coca-Cola products over a period of 21 years caused an estimated 8.8 ± 0.7 MMT of plastic pollution in aquatic environments, (11% of 54 MMT). The majority of Coca-Cola's marine plastic leakage was predicted to stem from their product sales in *East Asia & Pacific*, closely followed by the sales in *Latin America and the Caribbean* (Figure 15, Panel B). An estimated 13% of Nestlé products leaked into oceans, at 4.5 ± 0.3 MMT but the geographic distribution was less varied compared to Coca-Cola: Nestlé sales in *South Asia*, *East Asia & Pacific* as well as and *Middle East & North Africa* all contributed roughly equally to marine pollution. Only about 4% of PepsiCo plastic waste ended up in oceans, with the majority of the polluting mass originating from the *Latin America & Caribbean* world region. Panel B in Figure 15 visually presents patterns of the geographic distribution of plastic sales for each company. PepsiCo's sales focus on *North America*, whereas Nestlé has the largest presence in the *Middle East & North Africa*. Coca-Cola sold the most of its products to the *European Union (EU)* and in the *East Asia & Pacific* region.

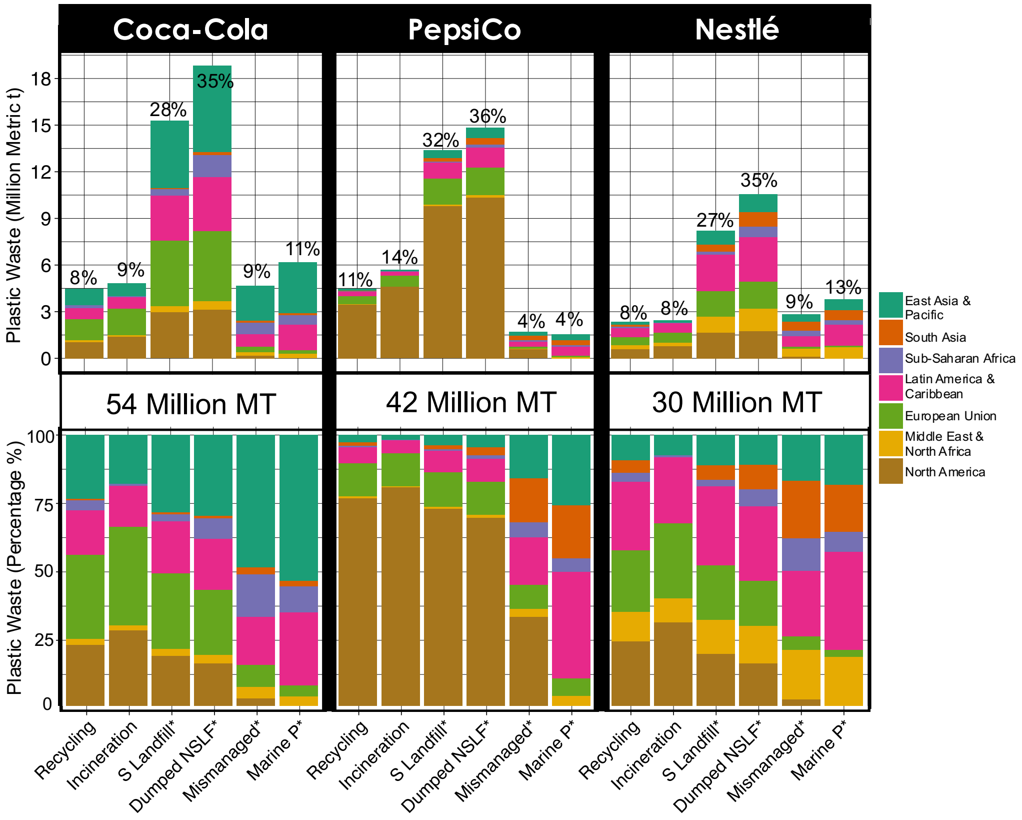

Figure 15. The mass (MMT) and percentage of plastic going into each end-of-life sink from each company organized by geographic region. A-B Mass flows from companies (organized by decreasing plastic waste mass), to countries (categorized by geographic region, organized by decreasing population) to waste end-of-life sinks (organized by decreasing environmentally sound value). (A) Coca-Cola, PepsiCo, and Nestlé produced an estimated 54 MMT, 42 MMT and 30 MMT of plastic waste respectively, over the last two decades as depicted by each square in panel A. That mass went into six end-of-life sinks. Each end-of-life sink was further stratified into by one of seven geographic regions (see legend) which represent a total of 185 countries. (B) The masses in panel A are scaled to the total mass of each end-of-life sink (scaled to 100%).

For every dollar of revenue made, the three companies produced 0.04 kg of plastic waste that municipalities and cities around the world then have to contend with and dispose of in environmentally sound ways. The average cost of collection and sorting of plastics globally was $298.75 USD/metric ton (Borrelle et al., 2020). This does not include the cost of landfill tipping fees and disposal fees. Thus, plastic waste from the three companies combines was predicted to cost taxpayers an estimated $1.8 B ± X.X USD annually. This annual cost is predicted to increase to $2.4 ± X.X B USD by the year 2050 with an extra 314 MMT (± 15 MMT) of plastic waste being added as modelled in (Figure 1), if packaging practices do not change.

Consumption of goods from Coca-Cola, PepsiCo, and Nestlé increase by income classification, suggesting that the wealthier the country the more is consumed in it. Currently, HI, and UMI income countries account for 75% of all plastic sales (Figure 2). Although LI and MIC income countries only buy 25% of the products that come in plastic from Coca-Cola, PepsiCo, and Nestlé, these countries that do not have adequate management infrastructure in place to manage the plastic waste post end-of-life. Figure 3 shows that 3.3 MMT of Coca-Cola plastic waste which have leaked into marine environments could have been curbed with better collection infrastructure in East Asia & Pacific. Latin America and the Caribbean is another global region prone to contribute to marine pollution, likely added by high tourism. Africa and Asia are anticipated to house 97% of the population growth that is expected to take place over the three decades, as predicted by the United Nations (United Nations, 2015). Lebreton et al., (2019) argue that a disproportionate burden of plastic waste will occur in coastal communities in those regions. We take that argument further; future markets for FMCG have been defined as Africa, and Asia (Coca-Cola, 2017). The expected plastic waste originating there is predicted to end up in those coastal regions that historically have shown low investments in the collection and accountability of product waste from FMCG packaging they procure through the three major beverage companies; thus, these massive future sales products are destined to enter oceans and cause pollution.

In fast-growing economies such as Sub-Saharan Africa and Asia, waste management infrastructure has been unable to keep pace with the strong economic growthA consequence of inadequate infrastructure is the dumping in non-sanitary landfills and mismanagement of waste. Approximately 36% ± 9% of plastic waste created by the the major three global beverage companies is predicted to have ended up dumped in non-sanitary landfill sinks, with another 11.9 ± 1.0 MMT being mismanaged, represented in Figure 2 as waste that is not recycled, incinerated, or sanitarily landfilled. Mismanaged plastic waste is often openly burned, thereby creating dioxins and other critical health threats that are estimated to contribute up to 29% of global anthropogenic emission sources (Azoulay et al., 2019). The CO2 emissions associated with plastics are also an increasing concern (Cabernard et al., 2022), and the slow biodegradability of plastics poses long-term pollution impacts more so than carbon sequestration benefits.

North American and the EU dominate the recycling, sanitary landfill, and incineration pathway, closely followed by high income countries in East Asia & Pacific (Figure 3). These infrastructures require large capital and operational investments that are not readily achievable in developing countries. Already, many cities around the globe are reaching their landfill capacity earlier than anticipated (Rosengren, 2020). Furthermore, the liquid and gas emissions from plastics in landfills often contain hazardous compounds (Reinhart, 1993; Roy, 1994), that are expensive to manage. Without proper remediation, leachate collection systems and long-term monitoring, landfills become non-sanitary landfills - accounting for the highest waste sink with 45 MMT ± 3.8 in our model (Figure 3) - a problem in both developing and developed countries to varying degrees (Morita et al., 2020).

Borrell et al. (2020) mention that even a three-pronged plastic waste mitigation strategy consisting of (i) reducing waste generation (e.g., bans on single-use plastics), (ii) improving waste management (e.g., capture and containment of plastics), and (iii) environmental recovery (e.g., clean-up), is not enough to stem the flow of plastic waste into global oceans at the targeted 8 MMT/ y. The assumption here is that the target will have to be met by global citizens. We fundamentally question the notion that countries and consumers are the most powerful actors to stop or even to take responsibility for decreasing or improving the waste management of single use plastics and plastic packaging and suggest that more fastidious actions can be taken by industry actors. The beverage industry in particular has an extremely fast turnover time, and thus the single-use plastics attributed to this industry are more likely to proliferate with growing markets and economies. Calls from activist organizations for consumer goods companies to curb plastic pollution have increased. A brand audit of plastic debris (qualitative assessment) found on beaches showed that over 90% could be traced back to the biggest multinational companies in the FMCG in the beverage sector (BFFP, 2019; Charles et al., 2021; Heinrich Boll Stiftung, 2019). To cap leakage of plastics into the world's oceans at 8 MMT/y, the required reduction rate of plastic waste needs to be 40% in HI, 35% in UMI and LMI and 25% in LI countries (Borrelle et al., 2020), targets that could be met more easily by the FMCG industry and specifically the beverage industry as demonstrated by the data presented here, than by individual countries and individual consumers, as an estimated 0.8 MMT/year of plastic waste ends up in oceans from just three companies.

The packaging industry is estimated to be worth $900 billion USD in 2019 (McDonald et al., 2001). FMCG companies spend between 1-4% of their revenue on packaging. That amounts to $1.9B to up to $7.8B USD in 2019 for C, P and N. Several commitments made by C, P and N include “making 100% of our packaging recyclable globally by 2025” and “use at least 50% recycled material in our packaging by 2030,” (Coca-Cola, 2021). Other major brands have similar commitments, ensuring a high demand for pure recycled materials, especially PET. Firstly, a reduction cannot be measured if the base value is unknown, emphasizing a need for public disclosure of plastic consumption by all FMCG companies. Secondly, in the USA, the FDA requires a written description from companies wishing to use post-consumer recycled plastic for food grade applications, with details such as waste source, recycling process and results of tests proving contaminant removal (FDA, 2022). In the EU “the proportion of PET from non-food consumer applications should be no more than 5% in the input (feedstock) to be recycled, (EFSA, 2022)”. To complicate things further, no recycling infrastructure currently exists to deliver on these commitments at the scale needed, as contamination and traceability issues bar re-entry of food waste plastics from going back into their supply chains. This is why most post-consumer PET is downcycled and not recycled. Thirdly, even including recycling materials into their products will be pointless if the packaging is still destinated to become pollution in land and sea without adequate collection infrastructure. Recycled pollution still constitutes unwanted pollution after all. If the FMCG companies want to keep their recycling commitments and retrieve their packaging costs, they will have to aid the waste management industry to trace their products post end-of-life. Uncollected packaging materials have a greater cost than the original beverage packaged inside it, especially if it becomes mismanaged or marine pollution. Arguably, the total cost of the packaging including the externalities, outweighs the value of the product itself.

Some argue that is in the waste is created by companies, because after all consumers are buying the product and not the packaging of a product. In the act of buying a bottle of water, the water in the bottle is bought– and not the bottle. The bottle is provided by the company. In the light of this argument an interesting concern arises most if not all literature defines people, the average citizen, as the “consumers” of plastic. In light of the above argument, one could argue that is indeed the FMCG companies that the true consumers of plastics, as they are the entities making the decision about the packaging of their product. A clear distinction of definition is made in this context, one that is pivotal to the plastics waste conversation (figure 16).

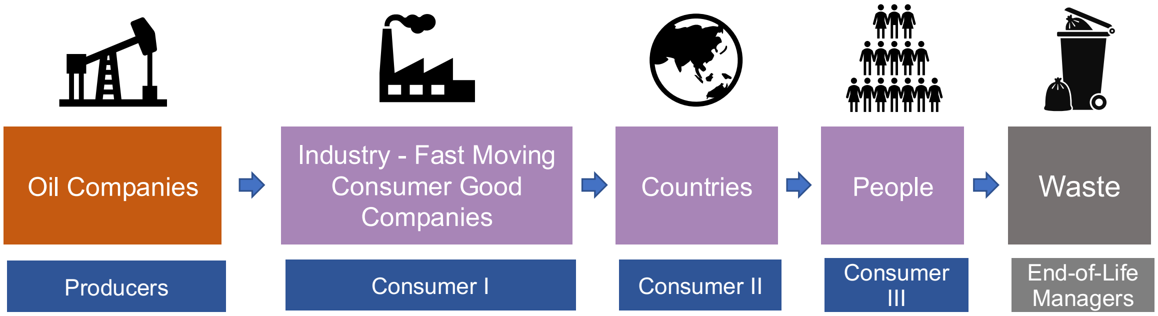

Figure 16. Pictogram of the sales of plastic, showing that Industry is the true consumer of plastic, not people.

China (UMI) previously absorbed up to 60% of PET waste, mainly from the USA and EU (HIC). The waste that is mismanaged or recycled in the EU and USA could potentially end up in other countries after collection in Western recycling centres and subsequent shipment to countries lacking both recycling and solid waste management infrastructure. This latter documented path of plastic waste also renders individuals partaking in responsible recycling efforts in the Western world indirectly complicit with the pollution of the global environment in countries receiving recycled plastics. Since the sword policy[1], Malaysia, Turkey (both UMI), and Vietnam (LMI) are among the few of the net importing countries, but the volume of their imports is uncertain (Brooks et al., 2018; Xu et al., 2020). The two main limitations of this study are that it assumes that the waste produced by these three companies is indeed single-use PET and PP and not any other type of plastics, and that this study does not account for the global waste trade. However, the assumption of unabated default use of PET and PP may not even represent a worst-case scenario, as a common greenwashing strategy of mixing petroleum-based synthetic plastics with a low percentage of plant based alternative plastics can create polymers that cannot be successfully reclaimed even if they are collected and taken into recycling centres.

4.3 Conclusion

Plastics offer considerable benefits to society but their current unrestricted and unlimited use in FMCG is not sustainable. Even if the recycling goals from FMCG companies were achieved, the pollution would simply stabilize at best, leaving pollution to perpetuate indefinitely to land and sea. Global plastic pollution is often portrayed as a wicked problem for which solutions remain elusive. However, the present analysis suggests that a disproportionate amount of plastic pollution could be avoided if FMCG companies would make an effort to retrieve the packing they sell in the various global regions that are vulnerable to plastic pollution leakage. Some 58% ± 8.9% of the plastics used by the three major global beverage corporations over the last 21 years have been either openly dumped, mismanaged, or indirectly contributed to marine pollution. Some 15.7 ± 1.3 MMT of

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[1] Sword Policy: Chinese ban on waste import from USA since 2017

plastics are estimated to have found their way into ocean sinks. Upper-middle, lower-middle, and low-income countries account for about 60% of the sales market for FMCG, but it is precisely these countries that do not have adequate waste management infrastructure to manage the plastic at end-of-life conundrum. In the past two decades, three companies dispersed 23 ± 12 MMT and 22 ± 1.9 MMT in the *East Asia & Pacific* and the *Latin America and Caribbean* region, respectively. Some 42.2 ± 3 MMT are estimated to have been deposited for the *North American* waste management system to handle. Many publications in the past years have focused on countries and people as the responsible drivers and empowered entities to reduce global plastic waste and pollution. Results of the present analysis suggest that a course change by a very small number of important players could help to make real progress toward the protection of global human populations, wildlife, and threatened natural resources. For real improvements to occur in curbing plastic pollution, multinational beverage and FMCG companies are key player dictating the demand, use and proliferation of plastics and with it the plastic pollution problem. It is in the hands of these companies to change current trends in plastic waste generation and pollution, with their global reach into more than 185 countries ensuring swift and comprehensive results or the lack thereof.

TRANSITION 4

The previous chapter assessed how much plastic waste was made by three multinational beverage companies: Coca-Cola, PepsiCo, and Nestlé. It was found that some 58% ± 8.9% of the plastics used by the three major global beverage corporations over the last 21 years have been either openly dumped, mismanaged, or indirectly contributed to marine pollution. Why has waste management failed to collect all these plastics from these companies and put it back into the system for re-use? What can companies do to ensure better management of their waste? Is waste even something that we as a collective humanity are entitled to make in the future? How do we re-think the system to make circular economy work in a practical way? The next chapter looks at pathways that stand in the way of a circular economy for the bottled beverage market. Chapter 5 is an opinion piece based on the authors collective years of experience working in the waste management industry in Singapore, Vienna, USA, and India.

CHAPTER 5

OPINION PIECE: BARRIERS TO A CIRCULAR ECONOMY IN THE BOTTLED BEVERAGE GLOBAL MARKET SECTOR

Waste. A simple, yet controversial word! The very notion of waste suggests the existence of inherently unwanted material flows, but this concept is foreign to *Nature* where each output represents an input for another process to create a complex, closed system of innumerable interconnected loops of matter and energy, big and small. Every feature of *Nature* has function and thus value. We humans on the other hand, have a long history of continuously creating and suffering from an inventory of human-made materials that become a toxic legacy with no conceivable function or value.

Disposed. This is an open-ended word that may pose more questions than it answers. Disposed, where to? For how long? At what consequence and cost? Matter has to go somewhere in the Earth system, its elemental building blocks may be rearranged but its overall mass will be conserved. Having witnessed the stark reality of landfills in eighteen countries and counting, my personal impression is this: The suggestive notion of disposed of, as being gone for good, is misguided. The manmade, non-biodegradable materials humanity expertly produces at ever accelerating rates may have been disposed of, but they continue to reappear and harm us, whether it is Agent Orange dating back to the Vietnam War, sewage sludge or millions of tonnes of consumer goods and packaging which continue to get deposited in land and sea, only to reappear to become detectable as health hazards in wildlife, food animals and humans alive or still developing in the womb. Landfills are a common feature of countries around the world: the proof of relentless consumption and a testament to our lacking commitment to sustainable manage our limited planetary resources. No matter if one looks to Africa, Australia or America, all continents carry these wounds, this evidence of humanity's reluctance to accept and integrate its activities into the working principles of the global life support system, planet Earth.

Recycling. Yet another word, that is not really understood by most people. *"Recycling"* is a conglomeration of actions that can look very different for different materials. For most plastics, the process starts with collecting, sorting, cleaning, washing, bailing, chipping, and melting before it is finally sold to be pelletized and then sold again to manufacturing industries, depending on their purity grade. This processing can span many months and many countries. Furthermore, the notion of something being "recyclable" is often a function of a city/ state and geography of the end markets, rather than an inherent judgement on the material itself and its intrinsic values. Technically anything can be considered "recyclable", because some niche and obscure technology exists to deal with it. Take for example the polystyrene eating beetle larva. This solution does not exist at scale, is not present in every city, but yet because a solution for polystyrene exists, a company can legally market it as recyclable. Thus, actually recycl***ed*** does not equal recyclable.

Solid waste management is one of the least disrupted and innovative business sectors in the USA. Humanity has managed to put a man on the moon, split atoms, invent social media and communally share anything from rides to rental homes, but astonishingly we have yet to figure out how to avoid and declare victory over the continuous creation of unwanted material streams we call *waste*. It interesting to note that the only difference between resource and a waste is that the first is composed of homogenous type of material, and the latter is just heterogenous material. To this day waste management is the least disrupted industry, still functioning much like it did in the 1950s, save for some machinal efficiency improvements.

Why is there such a lack of innovation and business evolution? It is because of the unspoken of but obvious conflict that maintaining and increasing profits at present require stagnating or increasing volumes of waste to be processed. In 2019, the publicly traded waste management companies made $112 billion USD (Companies Market Cap, 2022) and approximately 90% of this revenue came from landfilling (Waste Management, 2022). Landfilling is a lucrative business, why walk away from it and acquire new financial, logistical, and technical headaches in the process? If waste management companies were to invest into recycling that returns post-consumer materials right back to the manufacturing industries, they would be cannibalizing a hugely profitable business and capital investments.

In the EU such inertia to change is eliminated in part by nationalizing all landfilling activities with distinct public-private partnership contracts in place, so that private companies are contracted for operation and maintenance only of the absolute minimum of landfills needed. When tipping fees at landfills are collected by the government, these can be ratcheted up to foster innovation in waste volume minimization. In America in contrast, land is plentiful, most landfills are corporately or privately owned and operated, thereby creating a Golden Goose business model that disincentivizes waste minimization. Here, private ownership of landfills creates a powerful incentive for depositing more waste to increase profits. The more waste the US society at large creates, the more profits are being realized by landfill owners.

One could question why municipalities blatantly allow the above, when reducing waste from landfills is clearly stipulated in their mandates. Local municipalities are often caught between a rock and hard place. On one hand, it is their primary duty to keep a city waste free as mandated by federal and state law. Few things create political crises more reliably than the accumulation of smelly waste in dense population canters. If trash piles up and is not taken away, it is the local municipality and its decision makers who will be scrutinized and called out for failure. Thus, their first objective is to rid the city of accumulating waste by paying corporate waste management companies to haul the unwanted materials away. While municipalities want to divert waste from landfills, they are paying companies to do exactly the opposite, due to the overriding objective to keep the city clean and citizen protests away. Hired waste management companies are paid by the tonnage for hauling waste away from the city to the nearest landfill. Recycling and material recovery are perceived by the service provide as economic threats prone to cut into a lucrative business model.

Why does recycling not reap competitive profits? Contamination levels are high in baled recycled materials. For most manufacturers at the front of the supply chain, raw materials need to be at a purity level of 99.99% or better, in order to not compromise their products and value chains. Most recycling materials have a purity range of between 85-90%, which is not enough to re-enter the supply chain (LassoLoop, 2022). Plastics especially average a purity range of only 85% (Antonopoulos et al., 2021; Lase et al., 2022; Roithner & Rechberger, 2020), which is why most plastics are downcycled and not recycled. Used material markets with relaxed purity requirements are rare (e.g., mixed in asphalt for roadways, backing for carpets, and certain bags and shoes), thus limiting the market size for the sale of recyclables of intermediate and low purity. In 2017, China halted the import of waste from USA (Brooks et al., 2018). The true detail of the sword policy was that China now stipulated that the contamination of a recycling bale cannot exceed 0.5% (Detz, 2018). That means that means they are asking for a 99.5% purity grade, which is only procurable if you can make sure that your recycling bale has never touched a dirty diaper, banana peel, or lead acid battery.

Collecting ‘mixed recycling’ does not work. It is essentially mixed waste. It is like mixing ink with water and then trying to separate the ink from the water after the fact; it can be done, but it is expensive, inefficient, and creates secondary contamination. Since most consumers are confused about recycling, many materials end up in the waste stream that could be recycled. The vice-verse is true too, other material contaminate and diminish the overall value of recycling streams. Materials Recycling Facilities (MRF) use labour and machinery to sort through and extract valuables from a mixed waste stream. In the past five years they have incorporated artificial intelligence (AI) and robotics into the MRF to pick out valuable materials (most aluminium and metal). This is expensive and inefficient with low quality output. I argue that for the circular economy to be truly realized, we need to separate waste into homogenous resource streams at the hands of the consumer, and *then* apply technology to purify streams further.

Figure 17. Austrian recycling systems asks customers to separate white and coloured glass to be recycled. There is no mixed recycling. (Picture credit: Nivedita Biyani).

The average citizen is an undervalued but very important actor in the recycling challenge of the circular economy. Some 90% of U.S. Americans say that recycling is important to them (Carton Council, 2019). They don't like wasting or throwing things away (Cheah & Phau, 2011). Research in the social sciences shows that consumers want to recycle and that the feel-good factor about recycling is very important to them, as 61% are "very concerned" about having clean oceans, and 86% believe it's "important to take environmentally-friendly actions on a day-to-day basis," but more than 62% of them say that they are confused by recycling (Winterich et al., 2019). With more and more media coverage of the growing global plastic pollution crises, consumer demand actions and fast. Why isn't the infrastructure for recycling made easy, fun, and rewarding, in a day when literally everything else is. In a day and age where instant gratification has become a guiding principle of decision-making and life-style aspirations, real apathy can result from eco-friendly actions. Recyclability is questionable and the outcome of which is intangible. Consumers are frustrated, as there is no way to know if one's recycling actions mattered. To really make the circular economy of work for post-consumer plastic materials, recycling has to become fun, engaging, and social media adapted to deliver the instant dopamine rewards that today's lifestyle appears to demand.

Information equals power and the less data there is, the easier it is to maintain a money-making yet unsustainable business operation. There is more real time data available today on your heartrate, the miles you have walked in a day, and the websites you visited today, than the material contents of your refuse and recycling bin (black and blue containers, respectively, in the USA). Globally, accurate data on and for the waste management sector are lacking. The triumphs of technology and Big Tech have minimally touched and transformed waste management: a space and field that is not glamorous. White-collar workers in tech, banking, finance, real estate, communication, marketing, medicine, and law to name just a few sectors – they rarely suffer the indignity of being unable to rid themselves of an unwanted item or material. Out of sight, out of mind. At a city level, there currently exists no unified reporting structure that can adequately inform decision makers about the best waste/ resource management options and solutions.

Arguably, data on waste would be more valuable than the recycled material itself. Making waste traceable may indeed be viewed as a first and important step of bending the straight line of the linear economy. The concept of smart cities (Silva et al., 2018) and urban metabolism (Kennedy et al., 2011) are rapidly becoming a desired framework and data source for cities and municipalities, but not without pushback from those who stand to profit from business-as-usual in a linear (and wasteful) economy (Shahrokni et al., 2015).

But simply tracking waste is still not enough. To truly transition from the status quo into a circular economy, the waste chain must start to resemble the supply chain. Only then can it go beyond recycling to resupplying. This is an obvious truth and a fundamental challenge at the same time. The supply chain is long and global, involves millions of people and places, and yet the product travels down this chain of command fairly reliably to reach its destination. The supply chain is organized and traceable because it is valued. The global supply chain also has copious amounts of data regarding an item's material composition, location, transport, sender, and receiver. Before the pandemic, the supply chain was largely global, and it was traceable and organized. In sharp contrast to this stands the waste chain, which is short and local, disorganized, untraceable, heterogenous, and possibly intentionally obfuscated to protect those causing the mess. Thus, a critical step for the future of the circular economy is to make the waste chain as transparent, organized and structured as the supply chain already is today.

There is a high demand for pure recycled materials, especially 99+% PET and aluminum (Cullen & Allwood, 2013). FMCG companies have made numerous commitments to increase the post-consumer plastic contents in their packaging. Coca-Cola's pledged to "use at least 50% recycled material in our packaging by 2030." Nestlé, PepsiCo, and other major brands have proclaimed similar commitments (Coca-Cola, 2022; Nestle, 2021; Pepsico, 2019). However, currently there is no way to realistically deliver on these promises because of the contamination and traceability issues that bar re-entry of low-purity, post-consumer mixed plastics back into supply chains reliant on high purity precursors. In the USA, the FDA requires a written description from companies wishing to use post-consumer recycled plastic for food grade applications, with details such as waste source, recycling processes and results of tests proving successful removal of any contaminants (FDA, 2022). Currently, there is no way to trace and track where a particular bale of recycled material may have come from. If the FMCG companies truly want to keep their commitments, they will have to aid the waste management industry to tag and trace their products from the supply chain back to the re-supply chain. However, the FMCG sector is comprised mostly of food and beverage companies who are proclaiming a desire to incorporate more recycled materials into their packaging, but it is not clear whether this intent is genuine and business friendly; indeed, their primary concern is to minimize liabilities and risks from food processing, and using virgin materials from known sources (i.e., typically petroleum) also makes good business sense.

While making business sense for the companies and landfill haulers, solid waste disposal comes at a heavy cost for governments and citizen around the world. Annually, an estimated $205 billion USD of taxpayer money is spent on cleaning up cities (Hoornweg et al., 2015). The burden and risk that remain at the end of a product’s life suggest a need for a redistribution of responsibilities and a different approach to material end-of-life management; one that is not the responsibility of the public sector and citizens alone.

Human progress and waste production have long been regarded as intrinsically coupled to one another, such that advancements in the former lead to unavoidable increases in the latter; however, true human progress would be reflected in the production of less rather than more ‘waste.’ The philosophical ramification inherent to the definition of waste is that it is not possible to construct a sustainable outcome, as the implication of “not wanting or not valuing” is inherent in the definition of waste. Maybe a first consequential remedy to rid humanity of the waste problem is to rid our vocabulary from the ill-conceived term of waste. Or as Einstein put it, “No problem can be solved from the same consciousness that created it.”

CHAPTER 6

RESEARCH SUMMARY, POLICY IMPLICATIONS AND RECOMMENDATIONS

This chapter looks at the overarching research summary, policy implications and recommendations of this thesis. In Chapter 1 and 2, the data collected in this thesis demonstrated the presence in municipal sewage sludge of a broad spectrum of elements of substantial latent economical value. With respect to the composition, volume, and current and future management of SS management the key results are:

1. Some 56 were detected in North American sludge. A total of 28 industrial elements, 5 precious elements, and 14 rare elements were detected, ranging in concentrations from 10^{-3} and 10^{5} mg/kg dw.
2. Between 251 and 282 MMT of SS is expected to be produced in the USA from now to 2050.
3. American SS is estimated to contain an estimated 6.8 ± 0.5 MMT of valuable elements. Future reclamation of these elemental resources would be profitable if performed at a cost of <\$24B ± \$1.6B USD and could be aided today by separating SS from household and industrial waste in landfills.
4. Some 57 elements were found of the 60 tested for in Chinese SS. A total of 29 industrial elements,
5. China is estimated to produce between 819 - 910 MMT of SS between 2022 and 2050.

6. An estimated 14.9 ± 1.7 MMT of valuable elements will be sequestered in sewage sludge in the next 28 years in Chinese SS, worth a cumulative amount of $94 ± 20 billion USD.

Policy recommendation for SS management worthy of consideration based on this new information include: to ensure that the heavy environmental, social, and economic cost of mining metals are kept to an absolute minimum, it is essential that wastewater from industry is separated from household effluent. It is beneficial for companies to think of making products with end-of-life dissembling in mind, ensuring easier extractability of valuables and metals, that can go back into the supply chain. One very valuable suggestion is to separate industrial wastewater discharge from household wastewater discharge, as it seems probable that industry water effluent has a high metal loading due to their manufacturing processes. This actually poses a loss of value to the enterprise, as they are essentially discarding valuable element such as gold, silver, and palladium. A future research avenue is to test sewage sludge that has been procured only from industry and compare that to sludge that has been procured from household sewage and see if there are statistical differences in metal concentrations. From household sewage sludge it is important to extract phosphorus and nitrogen, as these are valuable for agriculture. It would be interesting to test the concentrations of phosphorus in household vs. industrial effluent, as it would be a further indication not to mix the two effluents and utilize the benefits that one has over the other.

Data amassed in this thesis on plastic packaging generated by three global FMCG companies include:

1. Just three companies are estimated to have made 126 ± 8.7 MMT of plastic dispersed globally, of which 15.6 ± 1.3 MMT (12%) were projected to have turned into aquatic pollution, creating estimated externalities of $13.6B USD annually.
2. Some 58 ± 5 MMT (46%) were estimated to result in terrestrial plastic pollution, with only minor amounts (9.9 ± 0.7 MMT, equivalent to 8%) deemed actually recycled.
3. Absent of change, the three companies by 2050 will add an additional 330 ± 15 MMT plastic mass to countries around the world, costing an estimated $8 ± 0.4 trillion USD in total.

An important policy outcome of this research is that all FMCG companies must disclose the material consumption of specific packaging materials such as metals, plastic, carboard, paper and multilayers mixed packaging every year. Platitudes that promises reductions have no weight if there is no baseline value to compare to. Furthermore, if the FMCG companies want to keep their recycling commitments and retrieve their packaging costs, they will have to aid the waste management industry to trace their products post end-of-life. For single-use plastic to be a realistic and integral part of the circular economy the first step would be to reduce its proliferation. Secondly, it is important to separate high value waste materials at a household level, stopping contamination before it happens. This ensures higher market rate for higher purity grades, that can go back into the supply chain. Thirdly, if plastics are to be landfilled in the absence of any recycling, then it is advantageous to combust it fully in controlled conditions to extract energy, reduce weight and volume, as they have a high calorific value. Landfilling of the remains in an inert ash is valuable to reduce the ecological burden and toxicity on land. Thus, a policy recommendation would be to make energy extraction before landfilling a policy directive in the USA. Furthermore, it would be valuable to prohibit landfills from being privately owned, as this would disincentivize landfilling. Finally, for circular economy to become a reality, it will be increasingly essential to track and trace waste and gather data of the origin and pathways of every material in the waste stream.

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APPENDIX A

SUPPLEMENTAL MATERIAL FOR CHAPTER 2 AND 3

Table 2. List of Elements Classified as Precious

Gold Au
Iridium Ir
Palladium Pd
Platinum Pt
Ruthenium Ru
Silver Ag

Table 3. List of Elements Classified as Industrial

Aluminum Al
Antimony Sb
Arsenic As
Barium Ba
Cadmium Cd
Calcium Ca
Chromium Cr
Cobalt Co
Copper Cu
Gallium Ga
Hafnium Hf
Iron Fe
Lead Pb

Magnesium Mg
Manganese Mn
Molybdenum Mo
Nickel Ni
Niobium Nb
Phosphorus P
Potassium K
Rhenium Re
Rubidium Rb
Sodium Na
Strontium Sr
Thallium Tl
Tin Sn
Titanium Ti
Tungsten W
Vanadium V
Zinc Zn

Table 4. List of Elements Classified as Rare:

Cerium Ce
Dysprosium Dy
Erbium Er

Europium Eu
Gadolinium Gd
Holmium Ho
Lanthanum La
Lutetium Lu
Neodymium Nd
Praseodymium Pr
Samarium Sm
Scandium Sc
Terbium Tb
Thulium Tm
Ytterbium Yb
Yttrium Y

Beryllium Be
Boron B
Cesium Cs
Lithium Li
Rhodium Rh
Tellurium Te
Thorium Th

Table 5. List of Elements Classifed as Other:

Uranium U
Zirconium Zr

Table 6. Enrichment Factor Categories (Barbieri, 2016; Muzerengi, 2017).

EF Factor	**Meaning**
EF < 2	Not Enriched
EF 2-5	Moderately Enriched
EF 5-20	Significantly Enriched
EF 20-40	Highly Enriched
EF >40	Extremely Enriched

Lab Methodology Details:

Nitric acid was either concentrated (~16 M) BDH Aristar Nitric Acid from VWR International (Manufacturer number 10101-VWNQ09; CAS 7697-37-2) or once distilled ACS grade nitric acid (manufacturer BDH, part #375000-80659; CAS 7697-37-2). Distillation occurred in a dedicated Teflon distillation apparatus (Savillex Corp., DST-1000 Acid Purification system). Hydrochloric acid was either concentrated (~12 M) hydrochloric acid (manufacturer BDH, part #257900-80401; CAS 7647-01-0) or once-distilled ACS grade hydrochloric acid (manufacturer BDH, Aristar Plus grade, catalog #87003-253; CAS 7647-01-0). Distillation occurred in a Teflon distillation apparatus (Savillex Corp., DST-1000 Acid Purification system) used only for distilling hydrochloric acid.

Trace metal grade 15 mL centrifuge tubes are VWR tube 15 mL Metal-free, catalog #89049-170 (VWR, Visalia, CA).

Teflon vials are from Savillex Corporation (Eden Prairie, MN, USA). Vials are either 15 mL vials with rounded interior (cat # 200-015-20) or 22 mL vials with rounded interior (cat # 200-022-20). Either of these vials take a 33 mm PFA closure (cat # 600-033-01). Smaller vials are also used, including the 7 mL standard vial with rounded interior (cat # 200-007-20) and 24 mm PFA closures (cat # 600-024-01). Smaller vials included the 3 mL standard octagonal body vial with a rounded interior (cat # 200-003-20) and 23 mm PFA closures (cat # 600-023-01).

Samples were analyzed by quadrupole ICP-MS (ThermoFisher Scientific iCAP Q, with CCT option). The instrument passed the mass calibration, cross calibration and daily performance reports for sensitivity, stability, oxide production ratio and doubly charged production ratio prior to sample measurement.

Calibration standards were made up from a mixture of single element certified ICP solutions. All samples were bracketed by calibration standards. An internal standard solution of 200 ppb Sc, Ge, Y, In and Bi was mixed online with samples to evaluate potential instrument drift and plasma suppression.

The LOD (limit of detection) is defined as three standard deviations of the blank run ten times. The LOQ (limit of quantitation) is defined as ten standard deviations of the blank run ten times. All measured sample concentrations were at least three times the LOQ and all reported data was 34 times the LOQ.

Table 7. Results of Statistical Testing Comparing Temporal USA Data.

Shapiro-Wilk Normality Test

p-value<2.2e-16

Null Hypothesis = The data is normally distributed

H1= The data is not normally distributed

The Kruskal-Wallis Rank Sum Test

Chi-squared= 3349.3, df= 4, p-value<2.2e-16

Null = No difference in the mean distributions in concentrations between the two sample years, by element.

H1= There is a difference in the distribution in concentrations between the two sample years, by element.

Effect Size Test

Y=Concentration of elements (mg/kg)

Effect size = 0.007834

Magnitude= Small

Post Hoc Dunn Test at alpha level of 0.05

26 = Not significantly different means

25 = Significantly different means

APPENDIX B

SUPPLEMENTAL MATERIAL FOR CHAPTER 4

Data Sources for Modeling Plastics

Sources for the plastic waste made by top three beverage companies worldwide in 2018/ 2019:

Ellen MacArthur Foundation. (2019). *The Global Commitment 2019*. 76. https://www.ellenmacarthurfoundation.org/resources/apply/global-commitment-progress-report

Sources for the revenue data collected from top three beverage companies worldwide from year 2000 to 2021:

Coca-Cola: Coca-Cola. (2022). Refresh the World. Make a Difference. *Business & Environmental, Social and Governance Report*, 35–72. https://www.coca-colacompany.com/

PepsiCo: Pepsico. (2019). *Creating more smiles with every sip and bite: Annual Report 2019*. 162. https://www.pepsico.com/investors/financial-information/annual-reports-proxy-information

Nestlé: Nestlé: Nestle, Annual Report (2000-2021), Available at: https://www.nestle.com/investors/publications

Sources for the sales data from top three beverage companies worldwide:

Coca-cola & Pepsi:
Global Softdrink Sales by Region 2012 and 2017, [Internet]. Statista. [cited 2021 Aug 13] Available from:
https://www.statista.com/statistics/232794/global-soft-drink-sales-by-region/

Nestlé: Nestle, Annual Report (2000-2021), Available at:
https://www.nestle.com/investors/publications
https://www.statista.com/statistics/268894/food-sales-of-the-nestle-group-by-region/

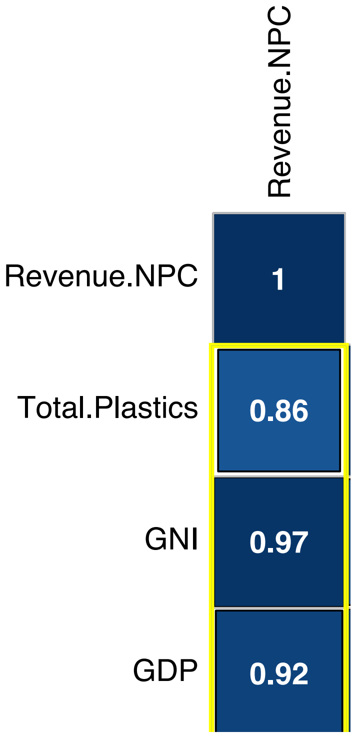
Sources for world polymer data:

OECD (2022), "Global Plastics Outlook: Plastics use by polymer - projections", *OECD Environment Statistics* (database), https://doi.org/10.1787/b9bae4d1-en (accessed on 24 June 2022).

OECD (2022), "Plastic waste projections to 2060", in Global Plastics Outlook: Policy Scenarios to 2060, OECD Publishing, Paris, https://doi.org/10.1787/d4a7a647-en.

World Bank data on countries, income level classification, geographic regions, and end-of-life:

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a Waste 2.0,: A global Snapshot of Solid Waste Management to 2050.* https://openknowledge.worldbank.org/handle/10986/30317



SI Figure 18. Correlation plot between four indictors and total revenue of three companies. Total revenue for three companies from 2000 to 2021 has a correlation coefficient of 0.86 with past global total plastics utilization estimates, 0.97 with past GNI data, 0.92 with past GDP data.

Equation 7. Data Analysis Part 1: Total Plastic Waste From NPC

To predict the dependent variable: total plastic polymer tonnage for three companies; Coca-Cola, PepsiCo, and Nestlé (SI Figure 3), a linear regression was done using the following equation. The amount of plastics used in the year 2019 was collected from public sources and was extrapolated backwards from the years 2000 and 2021.

$$\beta = \sum_{n=1}^{21} \frac{(R_n * P_{n-1})}{R_{n-1}}$$

β = Plastic used in n years (metric tonnes) per Company (2019)

R_n = Revenue, GDP, GNI, Plastic Polymer type used at n years

n = Number of years (2000-2050)

P_n = Plastic in metric tons at n years

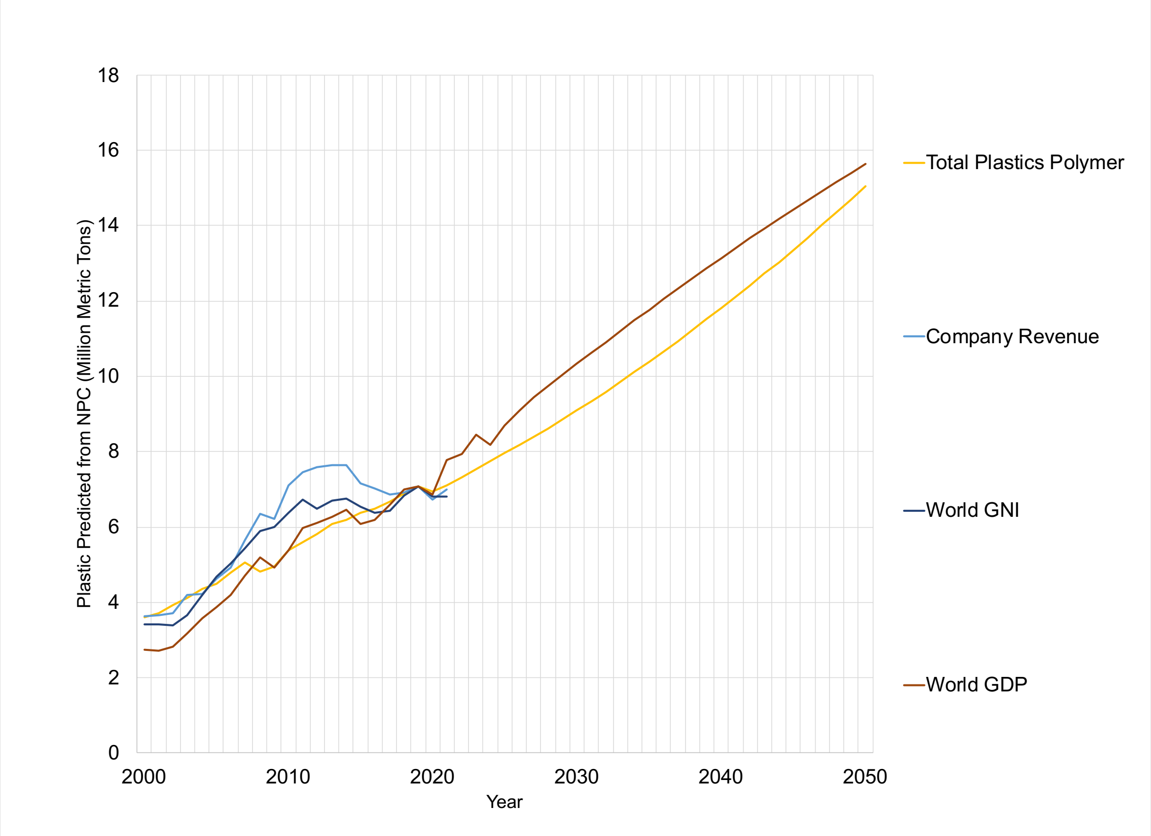


Figure 19. Estimated mass of plastic waste (MMT) produced by top three beverage companies from year 2000 to 2021, as a function of Revenue, GNI, GDP and Total Plastic trends. Except for company revenue, which was mined from annual reports, the rest of the data used to predict plastic waste tonnage, comes from the World Bank and the OECD (See SI page 1 for data sources).

Equation 8. Data Analysis Part 3: Sales by Region

Global soft drink sales, in millions of litres, by geographical region for the years 2012 and 2017 were collected and had to be normalised for the same geographical regions, and as consistent percentages for all three companies. Company C and P was split into the regions (S_{or}) “Americas”, “Europe, Middle East, and North Africa,” and “Asia, Oceania and Sub-Saharan Africa.” These three regional classifications were weighted by populations (2020) to expand the sales percentage into eight regions.” Company A sales already had the regions classified into eight regions. Company N (S_{or}) was split into four regions “Africa, Middle East and South Asia,” “Latin America”, “Europe,” North America.” Using the equation below we were able to use the sales percentage in original region category (S_{or}) weighted by the population to calculate sales percentage for new region category (β_{nr}) .

$$\beta_{nr} = \frac{(P_{nr} * \ S_{or})}{P_{or}}$$

$\beta_{nr} =$ Sales percentage for new region categories
$P_{nr} =$ Total population in new region category as of 2019
$S_{or} =$ Sales percentage in original region category
$P_{or} =$ Total population of original region category as of 2019

Equation 9. Data Analysis 4: Sales by Income ID

We had sales data by region for each company. In order to calculate the sales data for each income ID, we weighted it by variables found in "What a Waste" dataset by the World Bank; population by region and total tonnage of plastic found in particular region.

$$P_{inidr} = \sum \frac{\psi_{inidr} * \beta_{nr}}{\sum \psi_{id}}$$

$$\beta = \sum \left(\sum P_{inidr} \right)$$

$$\beta_{id} = \frac{\sum P_{inidr}}{\beta}$$

$\beta_{nr} =$ Sales percentage for new 8 region categories
$\psi_{inidr} =$ Total population/ msw / metric tonns of plastic in 8 region categories as of 2019 by income ID
$\psi_{id} =$ Sum of total population / metric tonns of plastic in by income ID
$P_{inidr} =$ Weighted sales percentage by income ID per region
$\beta =$ Sum of weighted sales percentage by income ID per region
$\beta_{id} =$ Weighted sales percentage by income ID

Equation 10. Data Analysis Part 5: End-of-Life Data

The "What a Waste" dataset is an effort by the World Bank to aggregate global data on solid waste management. This database covers 185 countries and includes data on waste generation, composition, collection, and disposal sinks as a percentage. This data set was combined with income classification data set resulting in a data set that had all the waste management information of the waste atlas by country, and each country was now classified into regions and income levels. We then proceeded to group each country by income level for each of the end-of-life sink, averaging the percentage for each end-of-life sink. To get the end-of-life sink by region we imputed the end-of-life sink percentage by income level into the original data set and then weighted each by region.

$$\mu_{il} = \frac{\sum_{n_{il}}^{1} \mathrm{x}}{n_{il}}$$

$\mu_{il} =$ mean by income level of end − of − life sink in percentage

$$\sum_{n_{il}}^{1} x = sum\ of\ data\ values\ for\ income\ level$$

$$n_{il} = number\ of\ countries\ \ in\ each\ income\ level$$

Since the original data 3 had 9 classifications of end-of-life sinks, we grouped them into 6 manageable classifications.

**Waste treatment-controlled landfill percent* was grouped with w*aste treatment landfill gas system*, as most controlled and scientific landfill systems have methane gas extraction capabilities. The average percentage was taken. This new grouping was classified as as *Sanitary Landfill*.

**Landfill unspecified* was grouped with *open dump* by averaging, as anything other than a sanitary landfill classifies as dumping. The new grouping was called Dumped Non-Sanitary Landfilling Denoted **Dumped NSLF*.

*Waste treatment *other* was grouped with *unaccounted* for percentage. The new grouping was termed **Mismanaged*.

The supplementary information on marine pollution by Jambeck et al., (2015) was summarized by income level and region to calculate the percentage of waste going to marine sources denoted by **Marine Pollution*. The end-of-life waste management data were averaged by income classification and then weighted by the population of the seven world region classifications to arrive at the percentage end-of-life sink for each of the seven world regions.

The percentage of 6 end of life pathways was proportionally recalculated using this equation:

$$\delta = \frac{\mu_{il}}{\sum \mu_{il}}$$

$$\delta = proportional\ mean\ for\ each\ end - of - life\ sink\ in\ percentage$$

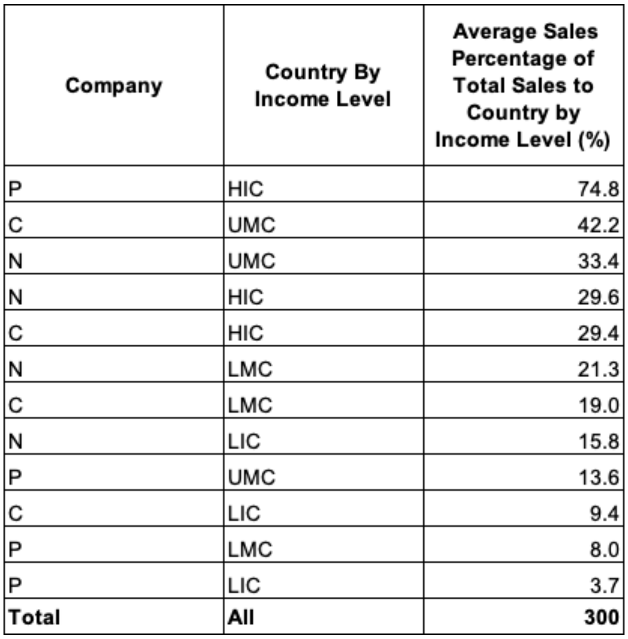
$$\sum \mu_{il} = sum\ of\ mean\ by\ income\ level\ of\ end - of - life\ sink\ in\ percentage$$

$$\mu_{il} = \ mean\ by\ income\ level\ of\ end - of - life\ sink\ in\ percentage$$

Table 8. Total plastic waste ending up in each country grouped by income level, totalling to the 126 million tons of plastic waste produced over 21 years.

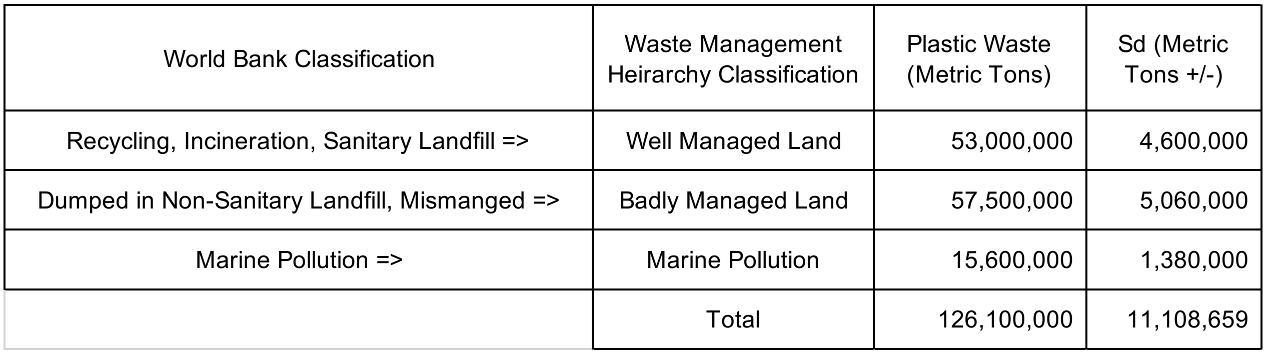
Company	Country Income Level	Plastic Sold to Countries Categorized by Income ID over 21 years (Metric Tons)	Standard Deveation (Metric Tons)+/-	Standard Error (Metric tons)
P	HIC	31,116,404	2,729,332	1,031,590
C	UMC	22,884,543	2,007,285	758,683
C	HIC	15,947,039	1,398,772	528,686
C	LMC	10,322,182	905,396	342,207
N	UMC	10,099,539	885,867	334,826
N	HIC	8,946,084	784,693	296,586
N	LMC	6,445,419	565,351	213,683
P	UMC	5,669,638	497,304	187,963
C	LIC	5,087,865	446,275	168,676
N	LIC	4,786,382	419,831	158,681
P	LMC	3,309,370	290,277	109,714
P	LIC	1,531,884	134,367	50,786
Total	**All**	**~126,000,000**	**~11,000,000**	**~4,000,000**

Table 9. Sales percentage of total sales from each company to each country grouped by income level.



Company	Country By Income Level	Average Sales Percentage of Total Sales to Country by Income Level (%)
P	HIC	74.8
C	UMC	42.2
N	UMC	33.4
N	HIC	29.6
C	HIC	29.4
N	LMC	21.3
C	LMC	19.0
N	LIC	15.8
P	UMC	13.6
C	LIC	9.4
P	LMC	8.0
P	LIC	3.7
Total	**All**	**300**

Table 10.Total plastic waste classified as per the official waste management hierarchy.



World Bank Classification	Waste Management Heirarchy Classification	Plastic Waste (Metric Tons)	Sd (Metric Tons +/-)
Recycling, Incineration, Sanitary Landfill =>	Well Managed Land	53,000,000	4,600,000
Dumped in Non-Sanitary Landfill, Mismanged =>	Badly Managed Land	57,500,000	5,060,000
Marine Pollution =>	Marine Pollution	15,600,000	1,380,000
	Total	126,100,000	11,108,659

Table 11.Total plastic waste over 21 years from each company accumulating in each end-of-life sink, organized in decreasing tonnage.

Company	End-of-Life	Plastic Waste Over 21 years Ending up in Each End-of-Life Sink (Metric Tons)	Sd (Metric Tons +/-)
C	Dumped NSLF*	19,440,742	1,705,217
P	Dumped NSLF*	14,982,371	1,314,158
C	S Landfill*	13,355,591	1,171,467
P	S Landfill*	12,672,972	1,111,592
N	Dumped NSLF*	11,390,167	999,072
C	Marine P*	8,813,397	773,055
N	S Landfill*	6,864,265	602,089
C	Mismanaged*	5,897,530	517,294
P	Incineration	5,148,714	451,612
N	Marine P*	4,552,331	399,301
P	Recycling	4,241,738	372,058
C	Recycling	3,776,031	331,209
N	Mismanaged*	3,761,654	329,948
C	Incineration	3,238,063	284,022
P	Marine P*	2,402,852	210,763
P	Mismanaged*	2,250,663	197,414
N	Recycling	2,123,507	186,260
N	Incineration	1,734,360	152,127

Table 12. Total plastic waste ending up in each country grouped by geographic region arranged in decreasing tonnage.

Company	Region	Plastic Sold over 21 years to Each Country Categorized by Geographic Region (Metric Tons)	Standard Deviation
P	North America	28,722,834	2,519,383
C	East Asia & Pacific	17,357,321	1,522,473
C	European Union	12,475,575	1,094,277
C	Latin America & Caribbean	10,305,910	903,968
C	North America	8,678,661	761,236
N	Latin America & Caribbean	8,476,831	743,533
P	European Union	4,995,276	438,154
N	European Union	4,843,904	424,876
N	North America	4,843,904	424,876
N	Middle East & North Africa	4,238,416	371,767
P	Latin America & Caribbean	3,746,457	328,615
N	East Asia & Pacific	3,632,928	318,657
C	Sub-Saharan Africa	3,254,498	285,464
N	South Asia	2,724,696	238,993
P	East Asia & Pacific	2,081,365	182,564
C	Middle East & North Africa	1,627,249	142,732
N	Sub-Saharan Africa	1,513,720	132,774
P	South Asia	1,248,819	109,538
C	South Asia	542,416	47,577
P	Sub-Saharan Africa	420,436	36,878
P	Middle East & North Africa	407,948	35,783
All Companies	**Total**	**~ 126,000,000**	**~ 11,000,000**

Table 13. Sales percentage of total sales from each company to each world geographic region arranged in decreasing percentage.

Company	Company	Region	Average Sales Percentage of Total Sales to Geographic Region (%)
Pepsi	P	North America	0.69
Coke	C	East Asia & Pacific	0.32
Nestle	C	Latin America & Caribbean	0.28
Coke	C	European Union	0.23
Coke	C	Latin America & Caribbean	0.19
Nestle	N	European Union	0.16
Nestle	P	North America	0.16
Coke	N	North America	0.16
Nestle	N	Middle East & North Africa	0.14
Pepsi	N	European Union	0.12
Nestle	P	East Asia & Pacific	0.12
Pepsi	N	Latin America & Caribbean	0.09
Nestle	C	South Asia	0.09
Coke	N	Sub-Saharan Africa	0.06
Pepsi	P	East Asia & Pacific	0.05
Nestle	C	Sub-Saharan Africa	0.05
Pepsi	N	South Asia	0.03
Coke	P	Middle East & North Africa	0.03
Pepsi	C	Middle East & North Africa	0.01
Pepsi	P	Sub-Saharan Africa	0.01
Coke	P	South Asia	0.01
Total	**All Companies**	**All**	**3**

Table 14. Plastic waste to each end-of-life sink from each company.

Company	End-of-Life	Plastic Waste (Metric Tons)	sd (+/-)	Percentage in each end-of-Life Sink
P	Recycling	4,479,097	392,878	11%
	Incineration	5,686,289	498,765	14%
	S Landfill*	13,383,176	1,173,887	32%
	Dumped NSLF*	14,823,480	1,300,221	36%
	Mismanaged*	1,710,882	150,068	4%
	Marine P*	1,540,210	135,097	4%
	Sum	41,623,134	3,650,915	
	Sum Rounded	~ 42,000,000	~ 7,000,000	

Company	End-of-Life	Plastic Waste (Metric Tons)	sd (+/-)	Percentage in each end-of-Life Sink
C	Recycling	4,458,662	391,085	8%
	Incineration	4,838,353	424,389	9%
	S Landfill*	15,285,291	1,340,728	28%
	Dumped NSLF*	18,810,997	1,649,980	35%
	Mismanaged*	4,659,356	408,689	9%
	Marine P*	6,188,970	542,857	11%
	Sum	54,241,629	4,757,728	
	Sum Rounded	~54,000,000	~ 5,000,000	

Company	End-of-Life	Plastic Waste (Metric Tons)	sd (+/-)	Percentage in each end-of-Life Sink
N	Recycling	2,364,430	207,393	8%
	Incineration	2,455,254	215,359	8%
	S Landfill*	8,210,416	720,165	27%
	Dumped NSLF*	10,550,627	925,433	35%
	Mismanaged*	2,833,684	248,553	9%
	Marine P*	3,790,355	332,466	13%
	Sum	30,204,766	2,649,369	
	Sum Rounded	~30,000,000	~3,000,000	

Table 15. Pollution values for all plastic from three companies

Pollution	Percentage	Tonnage	sd
Percentage Land Pollution	52%	57,723,127	5,063,103
Percentage Marine Pollution	12%	15,768,580	1,383,119
Percentage Total Pollution	58%	73,491,707	6,446,222

Equation 11. Ad-hoc Calculations Part 1: Cost to Taxpayer

Average global cost of collection of plastic: 156.5 \$/t (2018 USD) (Borrelle et al., 2020)
Average cost of sorting plastic: 142.25 \$/t (2018 USD)
Total cost of collecting and sorting 1 ton of plastic waste = 298.75 \$/t (2018 USD)
Cost* tonnage = 298.75 * 126,646,948 = 37,835,775,715 USD over 21 years
Average taxpayer cost per year = 37,835,775,715/ 21 = 1.8 Billion USD per year

Equation 12. Ad-hoc Calculations Part 2: Plastic per dollar revenue

7,088,925,318 kg* / 197,886,000,000 USD** = 0.04 kg per 1 USD
* total plastic produced by three beverage companies in 2019 (kg)
** total revenue for three beverage companies in 2019 (USD)

Equation 7. Ad-hoc Calculations Part 3: Cost of Plastic as Pollution in Oceans

Cost per tonne of marine plastic per year: 3300 to 33,000 \$/t (2018 USD) (Beaumont et al., 2019)
Average per tonne of marine plastic per year: 18,150\$/t
Cost* tonnage = 18,150\$/t * 15,723580 = 286,199,727,000 USD over 21 years
Average cost per year = 13,628,558,429 USD

BIOGRAPHICAL SKETCH

Nivedita has an undergraduate degree in Environmental Engineering from the (University of Nottingham, UK) and her master’s from Arizona State University (ASU) in Sustainability. Her Ph.D. is in Civil, Environmental and Sustainable Engineering (ASU), where her interests lay in applying circular economy principles for better end-of-life materials management. Nivedita has worked on sustainability and renewable energy for the United Nations in Vienna (Austria), with NGOs in India on slum sanitation, and for the Government of Singapore's Solid Waste Branch. She is Austrian and Indian, thus speaks fluent German, English, Kannada, and Tamil. She also has limited proficiency in Spanish and Hindi. She known that she will witness a world a waste-free world one day, where everything is a resource.