The Environmental Impact of COVID-19

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Introduction

Chloe Heath and Erica Svendahl

In March of 2020, the world came to a stop as the COVID-19 pandemic spread. Lives changed forever as schools, stores, offices, and many other establishments closed down and moved online. But how did this happen?

In mid-December of 2019, a group of people in Wuhan, found in China's Hubei Province, began to experience a respiratory illness not dissimilar to pneumonia, and regular treatments were not effective. These cases could be traced back to the Huanan Seafood Wholesale Market, which was closed in early January 2020 over concerns about the further spreading of this unknown virus. January 7th, 2020 it was declared a new virus by Chinese public health officials. In the following days, travel advisories came out for travel to Wuhan, cases started to be identified outside of China, and by the end of January, there were quarantine orders for travelers from Wuhan to the U.S.

By February 8th, over 1,000 people worldwide had died from the virus. Mid-March the world began to shut down. On March 13, 2020, the Trump Administration declared a nationwide emergency, and places of work and schools across the U.S. made the swift move online. Stay-at-home orders were issued across states, the Coronavirus Aid, Relief, and Economic Security (CARES) Act was rolled out, social distancing orders were put into place, and on April 3rd, 2020 a mask mandate was issued by the Centers for Disease Control (CDC).

While everyone was affected by the stay-at-home orders and mask mandates, some populations were affected disproportionately. In Chicago, "despite being about 30% of the total population, Black people account for 68% of the COVID-19 related deaths … and [were] dying of COVID-19 at a rate nearly six times greater than that of White Chicagoans, who account about 33% of the population and approximately 14% of deaths." [1].

This trend carried on throughout the COVID-19 pandemic as vaccinations were rolled out. The first vaccine was approved by the FDA on December 11th, 2020 for ages 16 and older. By November 2022, 80% of the U.S. population had been vaccinated, but Black people had the lowest rate of vaccination at 50% of the eligible population [2]. Bivalent booster shots became available around October 2022, and the rate of vaccination was skewed by race and ethnicity yet again, with Black and Hispanic people being half as likely to be vaccinated as White people [2]. Treatment was also skewed, with White people receiving antiviral treatments more often than Black and Hispanic people [2].

Unfortunately but unsurprisingly we see the same trend in COVID-19 deaths in the U.S. By January 2022, during the surge of the omicron variant, the death rates were highest for Black people at 37.4 per 100,000 and lowest for White people at 23.5 per 100,000 people. In addition, American Indian and Alaskan Native populations had a high death rate of 34.7 per 100,000, showing long-lasting racial inequalities [2,3].

By June 2022, the U.S. had a total of just under 85 million reported COVID-19 infections, and over 1 million deaths [1]. At this point, schools across the country had been fully or partially open for over a year with safety restrictions in place [4].

The health implications of COVID-19 go beyond contracting this deadly virus. Its potential long-term effects can be seen, felt, and measured through various areas of environmental health and chemistry. Environmental health contains 5 pillars: community health, food safety and hygiene, pollution control, occupational health and safety, and built environment [5]. Ultimately, changes to environmental chemistry caused by COVID-19 impact many of these pillars. Dissecting these changes allows us to better understand the long-term impacts of COVID-19.

Additionally, it's important to understand that, similar to the direct effects of COVID-19, its environmental effects are also felt disproportionally. One example of how the environmental impacts of COVID-19 disproportionately impacted individuals is indoor air pollution. With stay-at-home orders across the world, groups were confined to indoors. One study found that in Madrid, outdoor air quality improved, but indoor air quality plummeted, with particulate matter 2.5 ($PM_{2.5}$) increasing by 12%, and concentration of volatile organic compounds (VOCs) skyrocketing by 559% [6]. Volatile organic compounds can cause dizziness, throat irritation, damage to the central nervous system, and even cancer [7]. One of the major factors behind indoor air quality is ventilation. Older homes or homes that are not well-built are often not equipped with adequate indoor air ventilation, putting these individuals at a higher risk. Additionally, COVID-19 caused a drastic increase in medical waste, with an estimated 191 million pounds of medical waste produced from March 2020-November 2021. Many healthcare facilities, specifically in less developed countries, are unequipped to properly handle this waste, exposing workers to pathogens, needle sticks, and burns. Furthermore, communities surrounding landfills are exposed to contaminated air from burning this medical waste, as well as poor water quality [8]. These are just a few of many diverse examples of how the COVID-19 pandemic impacts individuals beyond contraction of the virus.

Ultimately, this underlines the impact COVID-19 had on environmental health. Even though the Public Health Emergency in the U.S. was declared to be over on May 11, 2023, there continue to be lasting effects of the COVID-19 pandemic [9]. Throughout this book, we will explore these impacts further by diving into COVID-19 related waste, its impact when handled properly, its impact when handled improperly, and greater societal effects.

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Chapter 1
Mask Life Cycle Analysis

Giulia Mantovani and Erica Svendahl

Introduction

2020 was an intense year containing many dramatic changes to everyday lives that were short and long term. With the COVID-19 pandemic people were forced to stay at home and events were either canceled or moved online. When we were allowed to leave our homes, we needed to wear a mask for protection. Masks started with fabric but soon enough we had access to single use medical/surgical masks with varying levels of protection.

The main function of a mask is to filter out large particles in the air which slows/stops the spread of disease. Masks protect us from droplets and sprays containing germs and, in this case, COVID-19 [1]. They have been essential to slowing the spread of COVID-19, but with the rise in single mask use there are new concerns related to their environmental impact.. This chapter will follow the journey of a medical mask through its material acquisition, production, transportation, disposal, and end of life. This type of setup is also known as a Life Cycle Analysis (LCA).

A typical single-use mask consists of an aluminum nose piece, polyurethane earloop and the 3 layers that make up the main body that covers the face. The main body is comprised of an outer layer Spunbond polypropylene (PP) 0.74 oz/yd^2 (textile unit – ounces per yard squared), Melt-blown PP non-woven 0.88 oz/yd^2, and Spunbond PP non woven 20 gsm on the inside [2]. The packaging will also be included in but not the main focus of this chapter. For context, the main components of packaging are the polyethylene films that cover each mask or group of masks and typically cardboard boxes the masks come in. You are more familiar with these plastics than you think. Starting off with polyurethane, it is a flexible foam plastic found in the earloop of your mask but also in places like in your couch cushions and bedding. Next, we have polypropylene (PP) which is versatile plastic that can be woven into the fabric of medical masks but also made of plastic containers and even car bumpers. Finally, the plastic that packages your masks, polyethylene, is one of the most commonly produced plastics and is what makes up supermarket plastic bags.

Material Acquisition

The first step of our LCA of single-use masks is looking at the impact of materials acquisition. A recent LCA provided a breakdown of the environmental impact of the acquisition of mask raw materials categorized by component [2]. As seen by Figure 1 w, the biggest impact is from the polypropylene as the spunbond is over 40% and melt blown polypropylene around 10% of the impact. Consequentlyover 50% of the environmental impact comes from polypropylene alone. For raw material acquisition we are mainly looking at the sourcing of the aluminum and polypropylene.

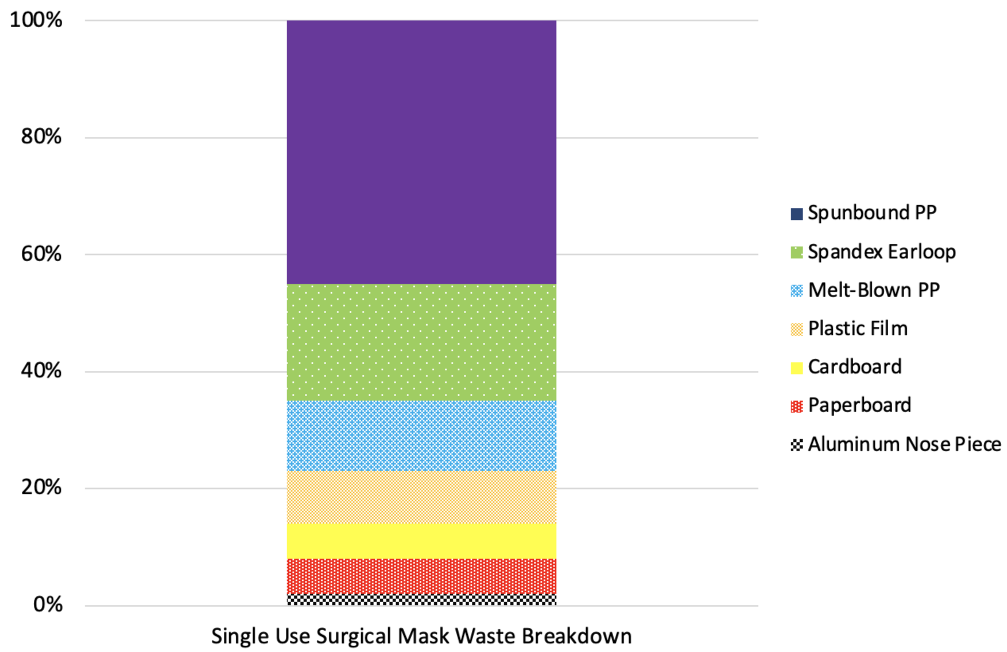

Figure 1. Breakdown of Impact of Single Use Mask by Parts [2]

Pure aluminum is not found in nature and is generally found as Bauxite which contains more than 50% aluminum oxide. The process of making aluminum, smelting, is not a simple one, as there are far more steps than just melting it down. Briefly Bauxite is first made into a powder and mixed with a natural mineral called cryolite. to then make aluminum by going through electrolysis (specifically electrolytic reduction), which is a common technique used to extract aluminum from from this mixture a direct electrical current is applied to free the aluminum. This process is called electrolytic reduction. . This production process requires a lot of electricity. Many aluminum smelters are aware of this and try to have their electricity produced by hydroelectric power plants like in Russia where 95% of their smelters run on hydroelectric power. Unfortunately, this does not ring true for all countries as places like China (leading Bauxite producers) have 93% of their aluminum electricity production generated by coal fired power plants. Coal fired power plants produce 23.6 tons of CO_2 per ton of aluminum while hydroelectric power only generates 4.4 tons of CO_2 per ton of aluminum. That is a 5 fold increase of carbon dioxide emissions into the atmosphere [3]. This is concerning especially with China being one of leading producers of aluminum and that was where most of the masks were coming from especially at the start of the pandemic.

Polypropylene (PP) is a polymer substance. To produce PP it goes through a polymerization process (either in the gas phase or liquid phase) to achieve an end product of plastic pellets. Polypropylene is a tough, rigid plastic which is one of the fastest produced plastics due to its ability to be produced into various molecular weights and crystallines [4]. This malleability makes it ideal for its use in single use medical masks. PP pellets are used in the production of materials [5]. In terms of mask production, the raw material isPP made into a non-woven fabric ready to be cut and assembled.

Let's go back for a moment and look more closely at where PP comes from. Polypropylene is considered a petroleum-based polymer, which means it is derived from petroleum hydrocarbons [6]. Therefore when looking at environmental impact, the refining of oil to produce propylene that is polymerized into polypropylenePP ultimately results in CO_2 emissions. The biggest producer of polypropene according to 2016 data is China, producing 20.2 million tons (over 18 million metric tons). For comparison, all of North America typically produces 8.6 million tons [7]. To get an idea of the amount of carbon emissions, we consider that one metric ton (1,000 kg) of PP produced results in the emission of 1.75 tons of CO_2 [8]. That means that more CO2 emissions by weight are generated than the weight of actual PP produced. When looking at the biggest carbon footprint contributors in the LCA of a mask, the top categories are raw materials processing and production. Combined material processing and production of the mask led to 87.6% of the carbon footprint of the mask [9]. A fun fact is that other studies have looked into the carbon footprint differences between a surgical disposable mask and a medical disposable mask. Interestingly though, surgical masks typically exhibited more carbon emissions, exactly 75.23% more emissions due to the increased packaging because they contain PE film (Polyethylene film also known as poly film) [9].

Production

Now it is time to actually build the mask itself. Medical Mask production is done through a machine line process and constitutes a couple different approaches. The medical masks are put together mainly by ultrasonic welds specifically when combining the three layers that make up the body of the mask. Ultrasonic welding is a process in which high frequency ultrasonic acoustic vibrations are used locally to put pieces together using pressure. There is also some stamping that is involved for the ear loops and putting on text and logos. One thing that all aspects of manufacturing rely on is electricity.

The electricity consumption of the body making, ultrasonic welding, and packaging of a mask. This is expressed with a unit of capacity known as Watt-hour (Wh) calculated per mask. Body making, ultrasonic welding, and packaging consumed 3.1, 0.3, and 0.6 Wh of energy per mask, respectively [10]. For a bit of context, the average cell phone battery has the capacity of 10 Wh [11]. That means on average the charge that your phone holds is equivalent to the energy needed to make almost 3 masks before packaging. To put that into perspective, in the year 2020, 52 billion medical masks were produced worldwide for a calculated 22 terajoules of energy [10]. To see more precisely what kind of impact that energy generation has on the environment, one needs to take a look at the different types of energy production and their pollution.

An important component in seeing the impact that electricity generation has is by looking at the breakdown of a country's different methods of energy creation. For example, looking at Turkey, a country with a large mask production, electricity by Natural gas 49%, Lignite (soft coal) 21%, Hard coal 7% and Hydropower 17% (source).

As a comparison, according to the EPA with data from 2016 the top 3 forms of generating electricity in the US are natural gas (34%), coal (30%) and nuclear (20%). Almost all aspects of electricity production have an environmental impact -. In general, if fossil fuels such as natural gas and coal are burned, there are greenhouse gasses, air pollutants which impact the planet. Burning also generates solid waste which is not good for the ecosystem and may produce further hazardous waste. The list goes on [12]. The EPA also has a helpful section on their website outlining several health effects that pollutants have and studies related to them [12].

According to the United Nations, the burning of fossil fuels generates a large portion of greenhouse gasses like carbon dioxide and nitrous oxide, which allows for the sun's heat to be trapped in the earth's atmosphere [13]. When fossil fuels are burned there are a handful of products that are released into the air during the combustion process. According to the US Energy Information Administration, some of the substances include: Carbon dioxide (CO2), Carbon monoxide (CO), Sulfur dioxide (SO2), Nitrogen oxides (NOx), Particulate matter (PM), and Heavy metals such as mercury [14]. These substances have effects on the environment in different ways:carbon dioxide is a greenhouse gas, sulfur dioxide can cause acid rain, and nitrogen oxides add to ground level ozones. Natural Gas and Coal powered generation of electricity are both considered fossil fuels which contribute to the effects of greenhouse gasses. Most people are familiar with natural gasses for heating and cooking in residential areas. The most common and well known natural gas would be methane (CH4). It is made from compression and high temperatures that allow for breakdown of its organic components (carbon) to create something specifically called thermogenic methane which is essentially methane that is generated through the heat of the earth deep beneath the crust. The method of extraction is drilling into the earth vertically with most reserves located in the Middle East. When natural gas is being used for electricity it is burned for energy [15]. When it comes to natural gas, burning them has less effect than burning of other fossil fuels on the environment with the main impact being the depletion of fossil fuels. Another big producer of electricity is the burning of the fossil fuel, coal.

When comparing the fossil fuels of burning natural gas and coal, natural gas releases fewer CO_2 emissions than coal when generating the same amount of electricity. One of the bigger concerns for natural gasses is methane, which itself is a big greenhouse gas. Over 200 lb of CO_2 is produced per 293 kWatt-hour generated of electricity as compared to the 117 lb of CO_2 per 293 kWatt-hour of burning natural gasses [14]. That is almost double the amount of CO_2 emissions produced by coal while generating the same amount of electricity.

Now the medical mask has gathered its materials and built the mask itself, it is transported on either a national or global scale.

Transportation

Throughout the pandemic, there were many different producers of masks, and the materials came from all over the world. Some countries made masks for themselves only, some made masks for the world, and others just bought masks. As the pandemic went on, these production roles shifted to the point that some dominant mask producers ended up importing masks. Regardless, masks were transported across the globe, emitting greenhouse gasses along the way.

We can look at the different distances each part of a mask travels throughout the country, ending with the whole mask and mask waste. Each mask, from production to being thrown away, travels an average distance just shy of 3,500 miles, or about the driving distance from Seattle, Washington to Miami, Florida. Traveling this distance in the U.S. by semi truck only, emissions are close to 161.8 g of CO_2 per mile. One trip for a mask could accumulate upwards of 566,300 g or over half of a U.S. ton of CO_2 per lifecycle trip[16]. All of this is to say, in order to get a disposable mask, transportation alone contributes to the warming of the planet in a significant way.

Table 1. As an example, mask transportation across Turkey [10].

Raw Material	Distance	Truck Size class
Spun bond polypropylene (PP) fabric	621 miles	15.7-31.5 tons
Melt-Blown polypropylene (PP) fabric	621 miles	15.7-31.5 tons
Nose Wire	155 miles	15.7-31.5 tons
Earloop	93 miles	15.7-31.5 tons
Packaging Material	186 miles	15.7-31.5 tons
Mask	1740 miles	>31.5 tons
Production and Packaging waste	31 miles	15.7-31.5 tons
Mask Waste	31 miles	15.7-31.5 tons

Turkey, however, is not the main producer of masks throughout the pandemic. At the beginning of the crisis, China already produced the most masks so they ramped up production in order to meet the global mask demands. This resulted in China producing masks for about half the global population. According to the US Department of Health and Human Services, it was estimated that more than 90 percent of masks sold in the U.S. at the beginning of the pandemic were manufactured in other countries [17,18]. As the crisis ramped up, China became conservative with exports, and other regions had to fill the gap. By 2021, Taiwan was producing 20% of the masks. An unexpected French company, Kolmi-Hopen, filled in the gap too [17]. Eventually, the U.S. started producing masks as well, even exporting some to China. If masks traveled by boat, each trip would emit on average 25 g of CO_2 per mile[19]. This means that a trip from China to the U.S.

could rack up as much as 167,500 g of CO_2, or ⅕ of a U.S. ton, just to reach the west coast. This is a fraction of what it would take to transport a mask around Turkey via truck, making production and transportation abroad seem more sustainable. We will now explore why this is not the case.

In January 2022, we saw some U.S.-based healthcare centers make their own masks [20]. in Illinois became self-sufficient in making masks for their staff. Some companies that normally manufacture other products like mattresses converted some of their production efforts to making masks. We also saw other American companies step up in production. For example, Armbrust American masks started becoming a staple around college campuses and across the U.S. In 2020, they opened up a mask-producing facility in Austin, TX. The result is a variety of masks being produced all over the U.S.

Local production is more sustainable because materials are transported shorter distances and there is more control over energy use. If you live in Kansas, a mask produced in Austin, Texas only has to travel 700 miles to get to you versus upwards of 7,500 miles if it came from China. However, remember in the Turkey example that even though all of those masks were produced and distributed in Turkey, they accumulated more transportation emissions than if someone in California were to use a mask that was shipped from China. Per mile, shipping anything via boat has less greenhouse gas emissions than shipping via truck. But, if the masks are being shipped across the ocean, they travel thousands of miles, racking up emissions via distance traveled. Therefore, traveling a shorter distance is ideal. In the Turkey example, their mask distribution could have been much more sustainable had there been more planning for local production and waste collection. If the total distance traveled decreased from 3,500 mi to anything under 1,000 mi, shipping via truck becomes comparable to a boat.

Control over energy production is the other component of local production that allows it to be more sustainable. A mask produced in the U.S. is more likely to be manufactured using cleaner energy sources. The U.S. gets about 60% of its energy from fossil fuels as opposed to China which generates about 87% of its energy from fossil fuels [21, 22]. If we look outside of China, U.S. production is cleaner because while global energy emissions are expected to rise, the U.S.'s emissions are going to remain flat [23]. Within local production, there is also a greater opportunity for lean manufacturing. Lean manufacturing means you can minimize waste while maximizing necessary production. So, while local production is more sustainable from an energy, labor, and inputs standpoint, we still have to be conscious of the social responsibility of manufacturers and take into consideration how they treat their workers.

Overall, masks were traded around the world and production roles shifted throughout the COVID-19 pandemic. The world came together to meet mask needs worldwide. As mask production continues, local production and disposal is more sustainable than the global trade of masks.

Use and Disposal

Fortunately, while wearing a face mask, there is no additional environmental impact. You take one out of a box, maybe it was wrapped individually and in that case, you throw away the plastic. But, for the most part, it sits on your face for a few hours, and in those hours, all of the production and transportation monetary and environmental costs are being put to use.

Before we transition to the mask's end of life, I invite you to think about all of the masks you wore throughout the pandemic. In the first few months, I hardly left the house. I wasn't the one in my family who grocery shopped, so I didn't have any particular reason to leave. About 6 months into the pandemic I moved and became the primary grocery shopper for myself, but that was the only time I left the house. Maybe I used one disposable mask a week. As time went on, college classes moved to be in person, but many required masks. I attended a year and a half of class while wearing a mask. If I went to class 5 days a week, for 4 quarters, I could have used 200 masks if I used one mask a day. Let's say we buy from an American manufacturer, on the Armbrust American website, one box with 200 masks is about $120. But that's only for class, assuming I didn't switch masks, and assuming I didn't wear any on the weekends.

But the biggest point is, I'm only one person and my mask wearing habits are not necessarily representative of the general population. Mask wearing varied among ages, occupations, location, and more. In July 2020, a survey was done to try and understand mask waste generation in the U.S., Australia, the UK, Sri Lanka, Singapore, and India. The survey looked at how often people wore masks, what kind of masks they wore, and how they disposed of them. First, 80% of respondents always wore masks at this point in the COVID-19 pandemic, and 16% said they usually do [31]. This totals to 96%, showing most people understood the importance of wearing masks. Of the people who wore masks, the majority were primarily surgical masks which we are exploring in this analysis. When disposing of these masks, 57% of respondents threw them away in the trash or a hazardous waste bin to be handled in a waste facility. 19% of respondents, however, admitted to littering and 10% admitted to burning their waste [31].

So, if millions of people around the world were wearing masks and disposing of them, hundreds of thousands of masks ended up in the landfill, but also hundreds of thousands ended up in the environment. Next, we will explore the implications of landfilling vs. littering.

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Think of the last time you took a walk in a public space or went for a hike in the past three years. Did you see any litter? How many masks did you see? Did the signature white and light blue pop out amongst the green brush? Unfortunately, mask litter has become a reality in a lot of places around the world. I remember hiking throughout the pandemic and seeing the progression of the mask litter. Some fresh, some starting to break down–a sad sight regardless.

If I really did use a whole box of masks just for class, that is about 1.8 lb of mask waste alone, assuming each one weighs 4 grams. That is not including the box itself or the plastic wrap the masks come in. If we include the box, we can call it 1 kilogram of waste per 200 masks. According to one study, "if even 1% of the masks are not disposed properly, this would result in as many as 10 million face masks per month dispersed in the environment. Considering the weight of each mask is about 4 grams, this would result in the dispersion of over 44.1 tons of plastic which poses a dreadful future."[24]

In Turkey, three of their largest cities, equating to about 5% of Turkey's population, are similar to the number of people that live in Los Angeles proper. The three cities, Nidge, Mersin, and Adana, add up to an area almost twice the size of New Jersey. Mersin and Adana are coastal cities and therefore have a lot of people traveling through them. Researchers found an average of 471 masks/mi^2 in all three cities, a greater density than expected. It was unclear where the masks come from, but polypropylene was the most common plastic in the masks. They identified that they have a problem and attributed it to education on what masks are made of. They stated people seem to believe masks are more similar to small articles of clothing rather than a sheet of plastic, which might influence how they treat the masks after use.

What doesn't end up as terrestrial litter could end up in a few other places. It is hard to discern sometimes where exactly all of the waste is heading, but as much as 75% of all COVID-19-related plastic waste can be found in oceans or landfills. Throughout the pandemic it has been estimated that 927,000 tons of medical waste including masks and gloves was produced per month, increasing the chances some waste would end up where it isn't supposed to. Chapters 2 and 3 further explore the waste streams of where medical waste is supposed to go and the effects on the ocean when it flows outside the normal waste stream. At the end of the day, the world was not prepared to accommodate the great increase in waste, whether that be physically with a lack of infrastructure or socially with a lack of knowledge on how to dispose of waste. As a result, there will be plastic around the world that enters into different ecosystems [25].

Once plastics end up in the environment, their behavior can change. "Environmental exposure can cause polymer aging and mechanical and oxidative decomposition of the plastic surface [26]. Some studies have also reported the changes in the infrared spectrum results due to weather conditions "[27, 28]. "Studies in the literature on polypropylene wastes have reported that polypropylene is not as durable as polyethylene and that changes such as breakage or deterioration occur in polypropylene "[29]. Changes like this alter the ways in which plastics interact with other living systems. If plastics break down to be small enough, they can be taken up into small lifeforms or even plants (see chapter 2). If they remain in larger pieces, they might be ingested by birds or other small animals. Regardless of how it makes it into a new system, the negative impacts remain. Effects can range from suffocating animals to changing how plants uptake nutrients.

So we have established that if even a small percentage of masks end up in the environment, that equates to tons of waste with large environmental consequences. Similarly, notice how the UN estimated that 75% of coronavirus plastic waste ends up in landfills *or* the ocean. Reporting it this way is confusing because how are we supposed to know how much waste ends up in either place? Waste belongs in the landfill, and reporting it this way makes it seem like the ocean is an acceptable second best. Chapter 3 explores this phenomenon more in-depth because there are many consequences to ocean plastic pollution.

Even if mask waste belongs in landfills, there are still concerns surrounding landfills. "Overloading landfills with PPE waste will pose certain concerns to the ecosystem, including space crush, plastic pollution, and leaching of toxic chemicals." [30] Landfills are also prone to leaking leachate. Leachate can be thought of as garbage juice. As the trash piles up, food and other trash gets crushed, and at the bottom of a landfill a pool of this juice forms. Most landfills are lined not with both concrete and some sort of plastic wrap in order to slow the transfer of leachate into the soil or water, but it isn't 100% effective.

Conclusion

Although masks have been a necessary and useful tool to help the world protect itself from the coronavirus, there is an associated environmental cost. They helped slow the spread of the virus and protected millions of people from debilitating sickness or death. However, there are environmental impacts that will last for hundreds of years post-pandemic. Next, we will continue the waste discussion by diving into biomedical waste.

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Chapter 2
Environmental Impact of Medical Waste

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Introduction

As COVID-19 spread and an unprecedented number of people became sick and required hospital admittance, healthcare systems became overwhelmed. One of the greatest challenges to the healthcare infrastructure was the need to protect staff from being infected by the virus. It was incredibly important to protect hospital staff so that they could continue to care for sick patients and so they didn't inadvertently spread the virus from one patient to another. Before vaccines were available, hospital staff relied solely on personal protective equipment (PPE).

Before COVID-19, when someone would go to the hospital they would be met by a nurse or physician's assistant in scrubs, maybe they would put on gloves or a mask depending on the procedure or the patient's reason for coming to the hospital. During the COVID-19 pandemic, patients were met by hospital staff wearing gloves, a disposable gown, multiple masks and possibly a plastic face shield or glasses. All of these items are considered PPE. Most types of PPE including gloves, face masks and gowns are disposable and replaced between each patient. PPE is essential in protecting healthcare workers from contracting COVID-19 and reducing the risk of transmission to patients and their families.

The combined increase in contagious patients seeking care and the increase in PPE requirements during the COVID-19 pandemic resulted in an increased amount of waste produced by hospitals. This waste, commonly known as COVID-19 related waste, consists of a range of materials, including PPE such as masks, gloves, gowns, face shields, and other protective equipment. COVID-19 related waste also includes medical equipment, and other various types of contaminated materials, such as tissues, and swabs used during testing. Medical equipment, such as ventilators, oxygen cylinders, and needles also contribute to the waste generated from hospitals.

The disposal of hospital-generated COVID-19 waste presents a significant challenge, as it might be contaminated with the virus, and improper disposal can lead to further spread of the disease. COVID-19 waste requires special handling procedures to minimize the risk of exposure to the virus. Hospitals must follow strict protocols and guidelines in disposing of COVID-19 waste to ensure the safety of healthcare workers, waste handlers, and the general public. Broadly speaking, COVID-19 waste can be classified as medical waste. Medical waste is defined by the World Health Organization as waste that is generated in the diagnosis, treatment or immunization of human beings or animals [1]. Legislation governing the classification, collection, transportation and disposal of medical waste varies across the world and is dictated by national governments and also by what infrastructure is present and able to manage the large amounts of medical waste.

Even before the COVID-19 pandemic, medical waste management was an issue of massive scale. The United States is the world's top producer of medical waste creating approximately 3.8 million tons of medical waste a year. Managing this waste is also very expensive with each ton of waste costing an estimated $800 to dispose of. Regulations, infrastructure systems, and finances in place to manage medical waste safely across the world struggled greatly with the increase in waste [2]. During the COVID-19 pandemic it is estimated that 16,649 tons of biomedical waste was produced daily and numerous studies concurred that the amount of biomedical waste increased with rising numbers of COVID-19 patients [3].

Generally speaking, globally and before the pandemic, there are two main methods of medical waste disposal for both infectious and non-infectious waste. The first is through landfills which are designed to contain waste safely and prevent it from contaminating the environment and posing a risk to public health. However, the disposal of COVID-19 related waste in landfills presents some risks such as potential soil and groundwater contamination and release of methane. The second medical waste disposal route is incineration, which involves burning waste at high temperatures. Incineration is effective in destroying infectious materials and reducing the volume of waste. However, incineration also has its drawbacks, as it can release harmful pollutants into the air, such as dioxins and furans, especially if waste is disposed of via open incineration [4].

Landfill Disposal

The COVID-19 pandemic has brought unprecedented challenges to the healthcare sector, leading to a surge in PPE usage in hospitals worldwide. While PPE has been crucial in preventing the spread of the virus, its excessive and improper disposal has raised concerns about environmental sustainability. We examine the different types of landfills and how they operate, environmental considerations, and the disposal methods for PPE waste before it reaches the landfill. According to the United States Environmental Protection Agency (EPA), there are approximately 2,000 active landfills across the country, serving as primary disposal sites for municipal solid waste (MSW). MSW refers to the everyday items that are discarded by the public. These landfills are designed with various environmental safeguards and monitoring systems to minimize potential risks to human health and the environment.

Types of Landfills

Landfills play a significant role in waste management and different types of waste are allocated into the various types of landfills. These include Municipal Solid Waste Landfills (MSWLFs), hazardous waste landfills, and one that is not technically considered a landfill, open dumps. Nearly all landfills can be essentialized under the term sanitary landfills. Sanitary landfills are known as any landfill that has precautions to prevent detrimental effects to the environment.

Municipal Solid Waste Landfill. MSWLFs are designed to handle non-hazardous waste, including PPE waste that is not contaminated and generated from hospitals. These landfills also handle all general and household trash. They contain lining systems that prevent the contamination of groundwater and other mechanisms such as regular sampling and testing of leachate, groundwater, and air emissions to prevent pollution reaching the environment. They are considered Subtitle D Landfills under the Resource Conservation and Recovery Act (RCRA). The RCRA was established on October 21st, 1976, and is a principal federal law in the United States that governs the disposal of solid and hazardous waste at the State and federal levels. The RCRA gives the EPA the authority to build a framework for waste management from a cradle-to-grave point of view. Targets in this act include transportation, treatment, storage, and disposal of waste [5].

Hazardous Waste landfill. Hazardous waste landfills are specifically designed for medical and/or hazardous waste, including contaminated PPE and other medical waste. They focus on materials that are potentially dangerous instead of collecting solid waste. Both kinds of landfills use lining systems to stop garbage from leaking into the environment. However, due to the greater likelihood of leakage and the greater potential dangers from hazardous waste, hazardous waste landfills often feature more robust liner systems. Typically the main difference is that hazardous waste landfills include at least two layers of leachate collection in the event that contaminants leak through the first layer [6].

Open Dumps. Open dumps are solely land where waste is disposed of with no contamination control mechanisms present and therefore not considered a sanitary landfill and not used for medical waste in the United States. Open dumping is prohibited in the United States under the RCRA (P.L. 94-580). This puts landfill and waste disposal under federal and National regulation as open dumping does not protect the environment, is prone to open burning, and is exposed to the elements and scavengers [7].

Disposal Process in Landfills

The disposal process in sanitary landfills involves several steps to mitigate environmental risks. The first step in the process is that the waste is compacted and spread in thin layers, allowing for better decomposition and minimizing air gaps. Liners made of impermeable materials, such as high-density polyethylene, are installed to prevent the migration of leachate into surrounding soil and water sources. Leachate can be defined as the water that percolates through the buried waste in the landfill obtaining the chemicals from the waste and leeches or draws out into the soil or into water supplies. The layers are normally arranged in this order: Compact clay is seated on the bottom of the landfill that was excavated, next a geomembrane layer is placed on top, and the leachate system is installed right above the geomembrane layer. Therefore, you could imagine in hazardous waste landfills that this layering system is multiplied based on the intensity of the load.

Additionally, gas collection systems are installed to capture and manage landfill byproduct gases, such as methane, reducing their release into the atmosphere. The collected methane can be burned to generate heat and energy, thus recycling this potent greenhouse gas and transforming it into a useful resource. To maintain sanitary conditions, the landfill is compressed on a daily basis. This compression not only prevents exposure to the air but also helps control odors and discourages pests from entering the site. Another aspect of landfill management is controlling rainwater and storm runoff, specialized storm pipes are installed within the landfill. These pipes are designed to divert and control the flow of water, minimizing erosion and preventing the runoff from spreading pollutants. By effectively managing water runoff, the landfill can reduce the potential for environmental contamination and ensure proper drainage.

Disposal Methods for PPE Waste Before Reaching Landfills

The management and reduction of the environmental impact of diverse waste types depend heavily on waste treatment. Before reaching the final destination of a landfill, waste goes through a comprehensive process. Interestingly enough, about 75 - 85% of the waste produced from hospitals can be categorized as municipal waste [8]. That means that only 15 - 25 % (by weight) is hazardous and needs to be regulated before reaching the sanitary landfills. Therefore it is vital for hospitals to sort their hazardous and non-hazardous waste to mitigate the amount of waste that requires treatment or ends up in landfills.

However, in the case that the waste must be treated, the garbage is initially prepackaged and delivered to a waste treatment facility for additional examination. The waste is then thoroughly investigated in the lab to ascertain its specific nature, which aids in choosing the best treatment approach. The treatment process has a number of goals in mind. In order to make toxic compounds harmless, it first attempts to neutralize contaminants found in the waste. PPE waste may contain materials such as plastics, synthetic fibers, and metals as described for masks in Chapter 1, which have varying rates of degradation. Over time, these plastics materials may break down and release microplastics into the environment, potentially harming ecosystems and wildlife.

Therefore physicochemical techniques are used to remediate waste that contains acids, heavy metals, or extremely poisonous liquids. A sequence of chemical reactions occurs inside a specialized reactor. This disinfection method effectively neutralizes the acids and removes pollutants from the waste by targeting and changing the basic molecular structure of the waste. By taking this action, the damaging elements are reduced, reducing their negative effects on the ecosystem [10].

Next, valuable fractions such as waste hydrocarbons and solvents are separated from the waste through centrifugation and distillation processes. This allows for their regeneration, making them available for future reuse instead of being wasted. Lastly, the method focuses on utilizing the waste's inherent energy potential in order to valorize it rather than simply trash it.

All garbage, however, cannot be totally processed and reclaimed. The last residue that cannot be processed further and inert hazardous trash are carefully managed. These materials are delivered to specific landfill locations, where safety cells are used to stabilize them. This ensures that even though they cannot be fully recovered, their impact on the environment is minimized through proper containment and management.

Landfills have been a prevalent waste disposal method in the United States and their function has helped to reduce non-hazardous and hazardous waste from the environment. The structures in place help to prevent methane gas and leachate from contaminating the environment. Other chemical sanitation techniques allow for easy extraction and recycling of waste. This chapter highlighted the current practices and environmental implications of landfills and waste treatment prior to landfilling. By embracing innovative approaches in the decontamination of waste prior to reaching the landfill and sorting waste between hazardous and non-hazardous, the United States can move toward a more sustainable future, reducing waste generation through landfills. However, a focus on separating out hazardous and nonhazardous waste in the hospital will help to reduce the amount of hazardous waste that enters our landfills and makes it easier on both staff members of the landfills and the environment.

Incineration

As an alternative to landfills, incineration is another waste disposal technique whereby waste is burned in large volumes then the ash is disposed of. About half of all hospital-produced medical waste, both infectious and non-infectious, was incinerated during the COVID-19 pandemic (Wisniewski, 2020). Incineration is used to reduce the overall volume of hospital waste and decontaminate infectious materials. The amount of hospital waste increased 10-fold because of COVID-19 (Bateman 2022). Although commonly used for medical waste, there is much controversy surrounding incineration due to its detrimental impact on the environment, air quality, and resulting effects on human health. Furthermore, the hospital waste must be transported to an incineration facility too, adding to the overall emissions created. The increased use of incineration during the pandemic has raised concerns about the potential environmental consequences and has highlighted the need to consider more sustainable alternatives for managing medical waste (Figure 1).

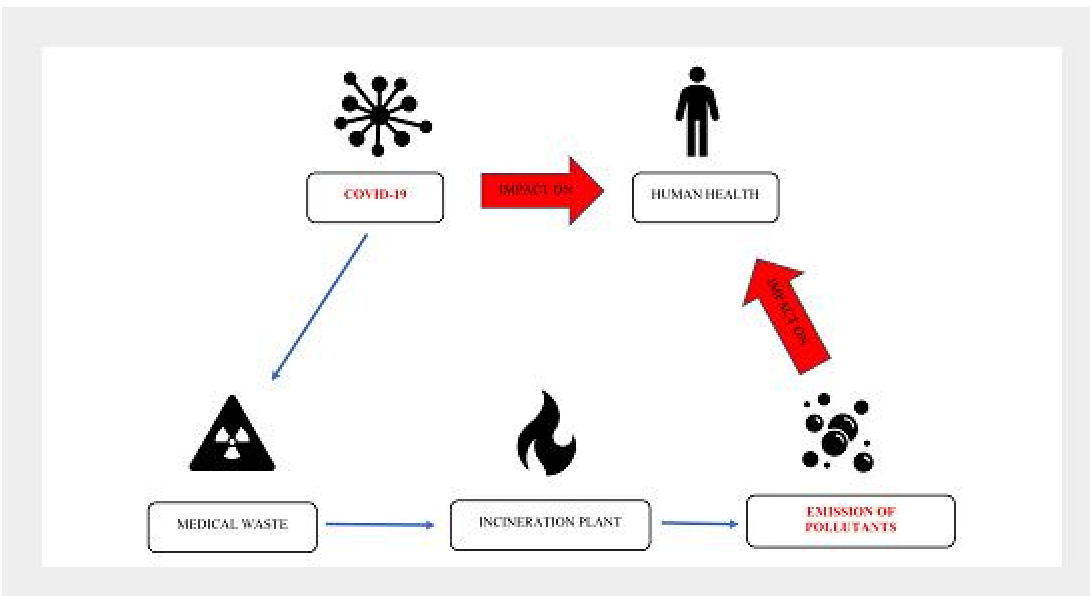

Figure 1: Sustainable Alternatives. https://doi.org/10.4209/aaqr.210399

Modern incineration techniques are hardly benign with toxic fumes and waste products need to be handled carefully. Medical waste is composed of 25% plastic, and when combusted can produce toxic and carcinogenic products (Gibbens, 2019). Not all methods of incineration are equal, though. 95% of all medical waste that is incinerated is done so using a special type of incinerator-controlled air unit (EPA). Controlled-air incineration ensures optimal combustion conditions by carefully regulating the air supply. This technique provides enhanced control over temperature and airflow, resulting in higher combustion efficiencies and reduced emissions. Controlled-air incineration is particularly useful for treating infectious waste, as it minimizes the risk of releasing pathogens into the environment.

Controlled-air incineration takes place in two stages (EPA). First, the waste is put in a "primary" container, which is heated to around ~1500℉ without any oxygen present. Oxygen is essential for fires to burn, so this technique dries out the waste completely and makes it more volatile without actually burning it, making it more likely to go to complete combustion in the second stage.

It is worth noting the difference between incomplete and complete combustion (burning) for materials. For most organic molecules, complete combustion results in the production of CO_2 and H_2O. Complete combustion takes place in the presence of enough oxygen; however, as molecules get bigger they need more oxygen to go to complete combustion. This is because larger molecules have more Van der Waal forces which increase the vaporization temperature of the material. Van der Waal forces are intermolecular attractions caused by dipole moments in a molecule. Take table salt, NaCl, for example. Sodium (Na) is giving its extra (negatively charged) electron to chlorine (Cl) to create an ionic bond. As a consequence, Na is slightly more positive, and Cl is slightly more negative, and the Na of one salt molecule will have an extremely small attraction to the Cl of another. These small forces are called Van der Waal forces. As molecules grow in size or concentration, the sum of all these small forces can become considerable. So, for medical waste, which is largely made up of polymers and large organic molecules, it is extremely difficult to deliver enough oxygen to the reaction. Therefore, incomplete combustion is much more common.

Incomplete combustion causes the breakdown of carbon-based compounds to stop before they reach completion, which produces a variety of cancer-causing compounds like polychlorinated dioxins and biphenyls (Windfeld and Brooks, 2015). These compounds can have detrimental effects on both human health and the environment. Most of these chemicals are known carcinogens, meaning that they affect people's DNA and cause cancer. Exposure to these chemicals can be deadly to humans and wildlife, which can greatly disrupt ecosystems exposed to the pollution. Chlorine in plastics like PVC or in bleached items like paper reacts with the carbon backbones of a variety of molecules to create these structures.

To combat the serious environmental hazards posed by medical waste incineration, a variety of new techniques have been employed. For example, some companies have employed a technique known as pyrolysis for specific types of COVID-19 waste, such as needles. Pyrolysis involves the decomposition of waste materials in the absence of oxygen (EPA). Pyrolysis produces "bio-oil", which can be used as an alternative fuel source. However, some controversy has arisen as to how environmentally friendly this technique actually is (Warzynski). Some experts claim that it actually uses more fuel than it produces, making the technique unsustainable. This is because bio-oil only contains about 50 - 70% of the energy that petroleum fuels do, meaning that fossil fuels are being burnt with no energy surplus in return.

In recent years, advancements in technology have also led to the development of waste-to-energy incineration systems (EPA). These innovative solutions combine waste treatment with energy generation, offering a sustainable approach to COVID-19 hospital waste management. Waste-to-energy incinerators combust the waste at high temperatures, producing steam or hot gasses that drive turbines to generate electricity. This dual-purpose approach not only reduces the volume of waste but also contributes to renewable energy production, making it a more environmentally friendly option. However, toxic side products are still created and need to be dealt with accordingly.

When selecting a waste disposal technique for COVID-19 hospital waste, it is vital to consider factors such as waste composition and volume. Additionally, strict adherence to environmental regulations and emission control measures is crucial to mitigate any potential negative impacts. By employing appropriate incineration techniques tailored to the specific needs of COVID-19 waste management, healthcare facilities can ensure the safe and efficient disposal of infectious materials, minimizing the risk of spreading the virus and protecting public health. However, much more work needs to be done in order to ensure that all incineration plants are equipped with the proper facilities to handle the waste.

A Look to The Future

The COVID-19 pandemic had wide-reaching effects and long-term implications that no one saw coming. In the case of medical waste, the pandemic highlighted the disparity between countries, the lack of sustainability in healthcare, and the need for better systems capable of protecting both people and the environment. National and global regulatory organizations have issued updated instructions and mandates specific to COVID-19 waste, which build on existing frameworks for medical waste disposal while considering the challenges caused by the pandemic. There are methods of medical waste disposal that have a lower environmental impact such as autoclaving. An autoclave is a steam and heat-based method of sterilizing medical waste and tools before disposal or reuse. Autoclaving has a relatively low environmental impact; it requires only 30 minutes at two times the earth's air pressure while heated to nearly 250 degrees Fahrenheit. Unfortunately, autoclaving technologies and other advanced, low-environmental-impact sterilization techniques were unavailable to many hospitals and only approximately 25% of medical waste is autoclaved [11].

Even hospitals with autoclaving capabilities still utilize landfills and incineration plants to dispose of medical waste as described earlier in this chapter. While both of these options are effective, they have adverse environmental effects. The number of COVID-19 cases and the amount of specific pollutants found in the air is connected. A rough correlation between the number of COVID-19 cases and the amount of sulfur dioxide and nitrogen oxide compounds (Figure 4) being released into the air was studied for Poland [12]. Both sulfur dioxide and nitrogen oxide compounds are considered indirect greenhouse gases. Indirect greenhouse gases affect the environment by affecting various essential aspects of our environment, like climate change. The number of COVID-19 cases significantly impacts the air quality due the volume of medical waste as we will further discuss in chapter 4.

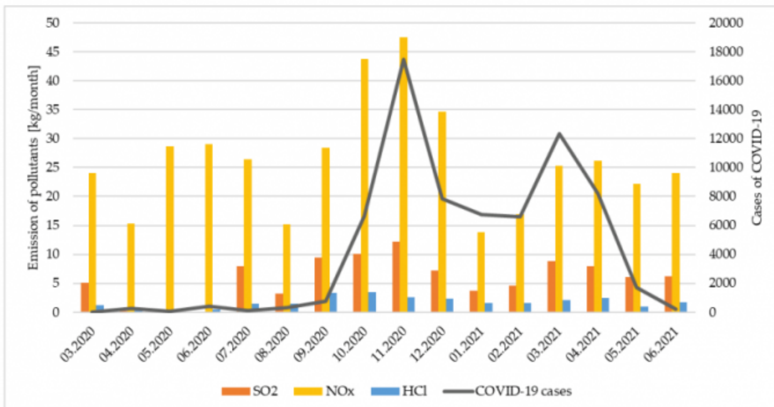

Figure 4. Overlaid graphs of number of COVID-19 cases and emission of various pollutants in kg/month [12].

At the height of the pandemic, emergency measures were taken that will have lasting impacts on the environment. Improper disposal of medical waste and leaks into the groundwater creates a risk of spreading the virus by introducing COVID-19 into the drinking water. In addition, more people getting sick from contaminated water leads to more medical waste, which, if improperly disposed of, leads to more contamination.

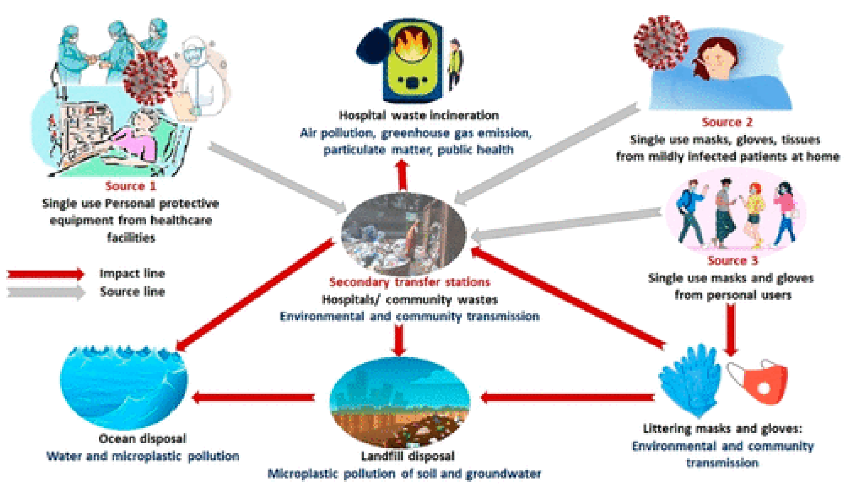

Figure 5. Flow chart describing different ways medical waste disposal affects the environment and human health [13].

Improper disposal of medical waste poses a risk to human health by becoming a route of infection, and it also poses a threat to the environment, mainly aquatic environments. There is a high risk of microplastics and other hazardous chemicals entering the groundwater and the oceans from landfills. The disposal of medical waste, biohazardous or not, harms our environment. During the COVID-19 pandemic, the impact on our environment also increased when the amount of medical waste increased significantly.

Despite these challenges and negative impacts, the COVID-19 pandemic has spurred scientists and researchers to closely examine the effects of medical waste disposal and processing on the environment, and published academic studies have begun to put forward suggestions for how to minimize the impact on air quality and water contamination [13]. These researchers' findings are already being used in hospitals and legislation. As a result, hospitals and regulatory agencies have developed much more strict and streamlined waste sorting policies that aim to mitigate the effect of COVID-19 and the future environmental footprint of the medical system[14].

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Chapter 3
Ocean Pollution

Lindsey Matulionis and Lexi McGowan

Introduction

COVID-19 has significantly increased the amount of plastic waste being produced and disposed of, specifically through personal and hospital PPE (Figure 1). Eventually, much of this waste washes up in seabeds and oceans. Plastic levels in the ocean were already an issue before the pandemic, but beginning in 2020, there has been a skyrocketing of medical waste (Chapter 2). Prior to the pandemic, 200 million tons of plastic were being produced and 5-13 million tons of this washed into oceans, with approximately 269,000 tons of plastic floating in the ocean [1].

During the pandemic, 65 billion gloves and 129 billion masks were being used each month [2]. Polymerase Chain Reaction (PCR) tests (which test if humans have COVID-19) have also been a large contributor to waste. To prevent cross contamination and the risks of COVID-19, plastic has been used for PCR tests, as it is 100% disposable. However, per sample, 0.82 pounds of plastic are generated. That means until August 2020, all patients who have been tested for COVID-19 via a PCR test have generated 15,400 tons of plastic residues [3]. With quarantine also came larger amounts of packaging waste from the increased need for delivery services [4]. In the United States, packaging plastics increased by 40% [3]. By 2021, unprecedented levels of plastic waste had seeped into oceans, weighing approximately 57,000,000 pounds (which is more than the weight of 2,000 double decker buses) [5]. Some researchers share concern over all PPE eventually working its way into the ocean, at some point during its disposal process [1].

Contaminated PPE was not properly disposed of early in the pandemic, partially due to unclear and insufficient information released to the public about the correct disposal process. There was also a lack of infrastructure capable of handling such levels of waste and a greater focus on containing the spread of the virus [6]. Consequently, the pandemic has taken the government's focus away from addressing environmental issues, which is seen by the pausing of some recycling programs in the U.S., Italy, and Spain. Now, in 2023, we have managed to get the virus spread under control, but PPE is still being found at high levels in our oceans.

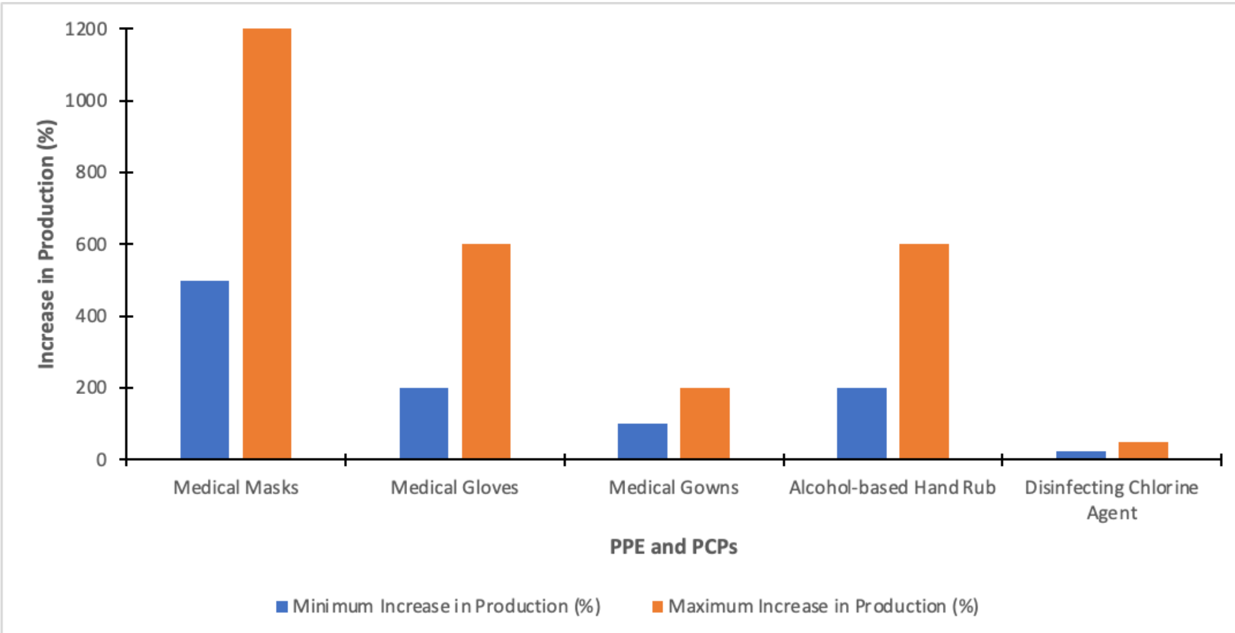

Figure 1. Increases in production of PPE and Personal Care Products (PCPs) during COVID-19 as of December 2020 [7].

Medical Waste Disposal and Ocean Pollution

Waste Disposal and Toxicity. Burnings, landfills, and incinerations, all of which are traditional ways of treating waste, are ineffective and unsustainable in the long term [7]. Much of biohazardous plastics, such as those thrown out of hospitals, eventually get incinerated, and account for about 97% of total plastic residues (remnants of broken down plastics). Non-biohazardous plastics end up in landfills, and account for around 3.2% of total plastic residues [3]. The burning of biohazardous materials leads to the production of toxic chemical pollutants, including gases that are harmful to human health [3]. More recently, there have been changes made to the incineration process that aim to better control these toxic gases. However, these processes are used more in developed countries, such as the United States and Europe, and other countries are still using old, harmful techniques [3]. With the COVID-19 lockdown, these problems have been exacerbated; with a collapse in oil prices (lowering the costs of oil products, such as plastics), it became cheaper to manufacture these materials than to recycle them [3].
Microplastics

Plastics are versatile, durable, strong, lightweight, and transparent. This makes them a distinctive material that can be used in many different settings [8]. They are also slow to degrade and persist for long periods of time, making them difficult to dispose of properly, so they subsequently accumulate. PPE waste gets broken down by both biochemical and physicochemical processes (winds, currents, UV radiation from the sun) when in the environment [7]. This results in microplastics (MPs), microfibers (MFs), and nanoplastics (NPs), all of which are considered non-biodegradable. They are easily transported around the world through wind and rivers, where they become further fragmented [7].

Microplastics (MPs) are defined as insoluble, manufactured, solid particles that are smaller than 0.2 inches in diameter. [9]. MPs found in aquatic environments, driven there by wind and atmospheric agents [8], can negatively affect marine life when in high concentrations. It is predicted that there will be more microplastics than fish in the oceans by 2050 [8].

Microplastics are made up of a variety of harmful chemicals, called additives, which are added during the production process to increase their durability [9]. Additives give plastics qualities such as color and degradation resistance from ozone, temperature, light, bacteria, etc. These may include fillers, plasticizers, antioxidants, UV stabilizers, lubricants, dyes, and flame-retardants [9]. UV stabilizers consist of cadmium, barium, or lead salts, which prevent thermal decomposition and oxidation. They are commonly aromatic organic compounds that absorb the UV radiation and dispel it as heat [10]. Dyes are fine powders that often contain heavy metals, and give plastics their color. Flame retardants contain chlorine, bromine, phosphorus, and aluminum hydroxide, which cool and protect the plastic from fires by inhibiting oxidation of flammable gases and forming an ash layer [9]. These additives are all important in the functioning of plastics, but they are toxic contaminants to the environment.

Marine Life. Microplastics in the ocean have a variety of effects on marine life health. Animals see plastics in the water and mistake them as prey and consume them. Turtles, for example, view PPE as food, but the straps of masks also risk entanglement and are a choking hazard. When the materials are broken down further, these turtles, as well as birds and fish, will ingest it. Subsequently, most animals die from the malnutrition that occurs from damaged stomach linings. In August of 2021, there was a face mask found in the feces of a sea turtle that was caught off the coast of Japan, subjecting the turtle to harmful additives [10].

Organisms also ingest the toxic contaminants that are embedded in MPs, which then get transferred through the food chain [8]. These include toxic compounds, additives, absorbed environmental contaminants, and heavy metals. Large marine animals ingest MPs directly from the environment and through eating other species that have consumed them. Once inside the body, MPs will either accumulate, enter the circulatory system and affect body tissues [7], or be excreted [8]. In body tissues, MPs can have severe effects on breathing, feeding, development, and reproduction. For example, blockages in the gastrointestinal system create a false feeling of fullness, leading to starvation, slowing of growth, reduced fertility, and reduced survival of offspring [8]. They may lower the immune response, change metabolic and reproductive processes, increase oxidative stress, increase cellular toxicity, and possibly lead to inflammation or cancers [8].

Polypropylene masks, a common synthetic polymer of MPs, were the most commonly used disposable face mask during the pandemic (Chapter 1), but they contain additives that interfere with the endocrine system and its associated hormonal functioning, making additives known endocrine disruptors. They also absorb harmful chemicals from the water. Researchers tested five types of face mask brands, and detected benzotriazole-type UV stabilizers in four of them. The concentrations found were comparable to those in plastic bottle caps, plastic bags, and food packaging.

Another study looked at the toxic effects of MPs on seabass [9]. Each test group had chemical contaminants in their food, but researchers added microplastic particles to the food of the experimental group, and compared them to the control group, which did not have microplastic particles in their food. They found a significantly higher level of polychlorinated biphenyls (PCBs) and brominated flame retardants, both of which are stabilizers in plastics, in the experimental group for up to 40 days after ingestion. When they looked at gene expression in the liver, they found that microplastics had worsened the effects of toxicity of the chemical contaminants.

Human Life. The increased levels of plastic waste found in the ocean due to COVID-19 has exacerbated the risks of plastics prior to the pandemic, and has led to greater consequences for the human body. MPs that result from COVID-19 medical waste breakdown may passively affect us, such as when they are dissolved in water. They negatively impact a type of phytoplankton, called Prochlorococcus, which provides 10% of the oxygen we breathe [1]. MPs can also directly enter the human body and impact our health.

Ingestion is the main mode of entry into the human body. We are subject to MPs and toxic contaminants through the food chain, where bioaccumulation and biomagnification occurs. Aquatic life at the lowest trophic level, such as plankton, may ingest MPs and other medical waste by-products, which are then consumed along the food chain and accumulate at higher trophic levels. This results in the seafood we consume becoming toxic [7]. This process also affects other products we consume, such as table salts [8]. MPs can additionally seep into the water we drink; researchers estimate we likely ingest around a spoonful of plastic each week [1]. Measurable amounts of nano- and microplastics were found in sugar, salt, alcohol, and bottled water. It is also estimated we intake approximately 0.176 lbs of MPs per day through fruits and vegetables, which gather MPs from polluted soil due to polluted waterways [9]. In one study, 20 plastic particles were found for every 0.35 ounces of human stool [9].

If a particle is less than 1/50th the width of a hair, it can enter the gut through endocytosis, where it is engulfed by the cell membrane and brought into the small intestine epithelial cells (a thin layer of cells covering the inner surface). These epithelial cells transport the solid waste from the lumen (inside of the intestine) to the circulatory system and tissues through paracellular persorption (a mechanical process that pushes particles through gaps in the cells) [9].

Microplastics also attach microorganisms once in the ocean, which can then enter human lungs and pose the risk of infection. The lungs have a thin barrier and large surface area, which allows particles to easily enter the circulatory system, and have toxic effects on the epithelial cells of the lungs. This can result in respiratory suffering, inflammation, and even autoimmune diseases. Reactions can also be expressed as asthma-like symptoms, diffuse interstitial fibrosis (scarring of lung tissue), chronic bronchitis, and pneumothorax (collapsed lung) [9]. The last main way MPs can enter the body is through the skin barrier, when it makes contact with products in the water contaminated with MPs.

Bisphenol A, phthalates, and brominated flame retardants, which are chemicals commonly used to make plastics for PPE and other medical supplies, disrupt our endocrine system (which is responsible for our hormones) and therefore negatively affect our organs and their responses to hormone signaling [9]. Endocrine disruptors have been connected with many conditions, including hormonal cancers, issues with reproduction (infertility), metabolic disorders, asthma, and neurodevelopmental conditions (such as autism), making them detrimental to human functioning. MPs have a higher surface area to volume ratio than plastics and are hydrophobic, which allows them to bind easily to other hydrophobic pollutants and heavy metals. These are then able to enter the body alongside the microplastics. Depending on the size of the MPs or MFs, there are differing levels of toxicity. Small MPs can reach organs, and some can even cross cell membranes, the blood-brain barrier, and the placenta. Many of the effects of microplastics on the body are not yet well understood, but their effects can differ based on physical and chemical properties, concentration levels, and growth of the microorganisms bound.

Chlorinated Disinfectants

The COVID-19 outbreak has led countries around the world to adopt new practices to control the outbreak and reduce the spread of the virus, including using large quantities of disinfectants, many of which contain chlorine. Thus, we will be primarily focusing on chlorinated disinfectants in this chapter. The quantities of chlorine disinfectants used is “several times higher than the recommended dose to control the outbreak” [11]. By 2020, at least 2,000 tons of disinfectants were distributed in Wuhan City, China alone [12]. The increased amount of chlorine disinfectants resulting from the pandemic raises concerns about water pollution and aquatic ecosystems health.

There are many ways in which chlorinated disinfectants can threaten aquatic plants and animals. First, chlorine can directly harm aquatic organisms by damaging their vital proteins and destroying their cell walls [12]. This means that disinfectant chemicals will react with proteins and prevent plants or animals from carrying out their normal metabolic processes. Bacteria, for example, are a vital part of the aquatic ecosystem as they transform nitrogen-containing compounds to a new form that can be used by plants and animals. Disinfectant chemicals interrupt this process, thus disrupting the entire nitrogen cycle in aquatic ecosystems [13]. Further, chlorine and chlorinated compounds can destroy bacterial cell walls and release their toxins into the environment. These toxins can have severe and chronic effects on aquatic ecosystems, as they are not meant to be consumed or absorbed by other animals [11].

Second, the chemicals found in chlorinated disinfectants can form harmful compounds by binding with other materials present in waterways. Such compounds have been found to be very toxic to aquatic life [12]. Trihalomethanes or haloacetic acids can form, both of which are toxic compounds. Further, disinfectants can combine with nitrogen to form chloramine or N-nitrosodimethylamine, which have been identified as carcinogens, a substance capable of causing cancer [12].

The chlorine in disinfectants can also undergo continuous chemical reactions with itself. The extensive use of chlorine results in accumulated disinfectant chemicals in aquatic environments[11].The compounds formed are hypochlorous and hydrochloric acids, which causes aquatic systems to grow more acidic. Because ecosystems thrive at a more neutral pH level, the increased acidity can partially or completely inhibit enzymes necessary for photosynthesis in plants. Ultimately, this limits growth of photosynthesizing plants, and reduces energy and oxygen production [11]. The lack of energy and oxygen in the aquatic environment threatens all life forms.

The increased levels of disinfectants in aquatic systems means an increased amount of chlorinated organic and inorganic compounds, which have "genotoxic, cytotoxic, mutagenic and carcinogenic effects" [11]. For instance, chlorinated hydrocarbons can accumulate in the adipose (fat) tissue of animals and have long-term, hazardous effects [11]. Also, chlorinated phenols can result in malformations and have negative reproductive effects on fish [11].

Chlorine and chlorinated compounds are toxic to aquatic organisms, but they are not the only harmful chemicals associated with disinfectants. The intensified disinfection processes during the COVID-19 pandemic increased the release of disinfection by-products (DBPs) [14]. Therefore, DBP levels in water have also significantly increased. DBPs form when disinfectant chemicals react with organic matter. DBPs are toxic and have many mutagenic (causes a mutation in DNA), teratogenic (causes fetal abnormality), and carcinogenic effects on aquatic life [14]. DBPs can damage photosynthesis processes and cause oxidative stress, which impacts proteins necessary for biological processes. Further, DBPs can contribute to algal blooms, which produce toxins that can kill fish, mammals, or other aquatic organisms [14]. Algal blooms will be discussed in more detail later on in the chapter.

The danger of chlorinated disinfectants is apparent. Further, disinfectants are usually contained within plastic bottles and containers. With an increased demand for disinfectants, there is a correlated increase in plastic production and disposal. Thus, the increased usage of disinfectants during the pandemic has amplified the dangerous effects of disinfectant chemicals, and the hazardous effects of plastics.

Toxic Chemicals

Plastics and Toxic Organic Chemicals. Given the high surface area to volume ratio of MPs, they are very good absorbers and transporters of toxic chemicals [15]. These chemicals make their way to aquatic environments, where they attach to plastic surfaces, affecting plants and animals [16]. Due to the durability of plastics in the ocean, more chemicals accumulate onto their surfaces the longer they are present in water. The vast amount of macroplastics and microplastics in the ocean indicates the many opportunities for toxic chemicals to absorb to their surfaces.

There are three ways in which plastics can be a vector for toxic chemicals. First, chemicals can attach themselves to the plastic, like a magnet. The characteristics of plastics make them an enticing surface for chemicals to attach to. Plastics are useful as containers and waterproof packaging, because plastic is apolar—it has no electrical polarity [15]. This makes plastic prone to non-polar and hydrophobic substances. Second, some plastic additives are not strongly bound to plastic polymers, meaning they can be released from the plastic into the environment and into organisms [15]. Third, plastics can spread pathogens throughout water environments, exposing animals to a variety of health hazards [17]. MPs can attract small organisms to its surface, some of which can be harmful to aquatic species. Due to the durability and persistence of MPs in water, plastics travel over large areas which results in the spread of these potentially harmful organisms. One study found a bacteria, Vibrio, on microplastics, which can cause diseases in humans and animals. In another microplastic sample, cholera was found, another bacteria capable of causing disease [17]. In places with a lot of plastic waste and poor sanitation, this can have great consequences on aquatic organisms and humans.

Floating plastics in particular can absorb persistent organic pollutants (POPs), which include polyaromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs) [16]. Due to the low solubility and non-polar characteristics of POPs, they can attach to plastic surfaces quite well. However, POPs can resist degradation and as they accumulate onto plastics, they quickly become harmful. These organic pollutants can accumulate in animal fats and animal tissues and have mutagenic, teratogenic, or carcinogenic effects. Overall, in tandem with MPs, the negative effects of POPs could be doubled [16]. Once POPs enter aquatic animal tissue, they affect many different systems. For example, reproductive, developmental, immunological, neurological, metabolic and endocrine systems can all be disrupted [18]. This means that POPs can induce diseases in many different systems within an aquatic animal, some of which can be deadly.

POPs have been reported to be at toxic concentrations in many different fish, demonstrating that organic toxins are concentrating in aquatic systems through microplastics and ending up in marine animals [18]. Their health effects are severe, and with increasing levels of plastic entering our ocean due to COVID-19, there are many more opportunities for these toxins to harm aquatic plants and animals.

Plastics and Heavy Metals

Plastics and MPs also have the ability to attract and absorb heavy metals, which introduce a new set of health hazards to marine life. Metals can be used in the manufacturing of plastics and eventually enter coastal waters. Plastics can attract and concentrate these metals, which can then contaminate waters or enter aquatic animals that accidentally ingest plastics [19]. In aquatic environments, heavy metals such as iron, lead, copper, zinc, and cadmium have been detected on plastic surfaces [16]. While many other heavy metals are present in water and have their own hazardous effects, these five metals will be our focus.

As plastic degrades over time, the surface area increases. This means the longer plastic is in the water, the more metal that can become attached to it [19]. Furthermore, this time in the water gives biofilms the opportunity to grow. Biofilms are collections of microbial cells assembled on a surface that metals can attach to. Thus, the formation of biofilms also increased the amount of metal present on a plastic surface. A biofilm saturated with toxic metals on a plastic could become an ecological health problem. MPs are easily ingested by aquatic life, and now are also bringing metals and harmful biofilms into aquatic systems [19]. Plastics, biofilms, and metals are all quite dangerous, but when in tandem with one another, their effects are further amplified.

Once MPs and heavy metals are exposed to marine life, a series of effects can occur. Cadmium, of particular concern, affects the chemical makeup of blood and affects immunological indicators. Protein levels can be reduced, and triglyceride and cholesterol levels can be elevated, indicating that immune system levels are reduced.

This makes aquatic animals more susceptible to infections and death [20]. Cadmium can also be deposited in the kidney and liver, introducing disease to the animal [20]. Lastly, chronic exposure to cadmium can result in growth, reproductive, developmental, immune, and behavioral changes in aquatic organisms [21].

Other heavy metals have severe effects on aquatic life as well when accumulated onto plastics. Copper can be highly toxic to certain fish species due to its ability to depress the immune system and damage gills, kidneys, and other organs in aquatic animals [22]. When zinc, an essential trace element in bodily systems, reaches a toxic level, it can kill fish by destroying gill tissue and inducing stress responses [23]. High concentrations of zinc can also alter growth factors, affecting how fish develop [24].

Mercury and lead are two more examples of dangerous heavy metals. Mercury can have teratogenic and neurotoxic effects, as well as reproductive toxicity which can cause harm to cells, tissues, proteins, and genes [25]. This ultimately affects how animals survive and grow. Mercury can be deadly as it greatly interferes with biochemical processes within marine species. Lead affects different stages of development, from fertilization to larval development [26]. It can also affect the nervous system of marine animals by damaging brain cells [20]. Lastly, varying levels of acidity affect the solubility and distribution of lead, meaning it can be more toxic to marine animals in different areas of the ocean [26]. Nevertheless, when present in high concentrations on microplastics, lead can be very dangerous.

While there are many other heavy metals that can be harmful to marine life, it is clear that heavy metals can be quite dangerous. Because heavy metals are toxic to marine life, they can also be damaging to humans through the food chain. As we consume seafood, we are also ingesting the microplastics and toxic pollutants consumed by marine life [27]. The combination of microplastics and heavy metals can have disastrous effects, from the bottom to the top of the food chain.

Food Waste

The pandemic has greatly disrupted the food system, increasing food waste in numerous ways [28]. For example, when the majority of dairy buyers across the world—like schools and coffee shops—closed due to the pandemic, the dairy industry had a surplus of milk. This ultimately led to the disposal of huge quantities of excess milk, which was a great loss for farmers and the dairy industry [28]. Onions are another example, with around 40% of them ending up in restaurants. Once restaurants closed due to the pandemic, large quantities of onions were wasted [28].

No amount of planning could prepare food operations for the sudden changes COVID-19 brought. Many restaurants closed during the early days of the pandemic and had to throw away large amounts of food [28]. As restaurants began to re-open, there was a lot of uncertainty around the demand for their services. The unknown of what to expect also increased food waste, as some restaurants overestimated how much food was necessary [28].

Food waste has not only increased in restaurants, but also at the retail level. Grocery stores were greatly affected by COVID-19. With the pandemic promoting social distancing and staying at home, stocked perishable products like fruits and vegetables went bad and were thrown away [28]. On the other hand, many people would stockpile food in their homes to avoid necessary grocery store trips, but this mismanagement of food stocking led to increased food waste, as consumers were not able to eat all of their food quickly enough.

Food waste has a large impact on the environment, oceans in particular [29]. First, food waste can disrupt the predator and prey balance of aquatic ecosystems. Predators have the opportunity to consume food waste over their usual prey, and their diet begins to consist of food scraps discarded by humans. This causes an increase in the predator population, and a decrease in the prey population [29]. Specifically, a study taken place in Monterey Bay, California revealed that food waste directly "impacted the delicate balance of the coastal food web between the local seabird, Western Gull, and its prey, the steelhead trout. The Gull had its diet shifted towards the abundance of [human food waste], resulting in an increase in Gull population. Increased predation pressure on steelhead trout resulted in a drop of trout population. Other fish-eating birds around Monterey Bay were forced to prey on juvenile steelhead trout and move down the food chain to survive. This consequently resulted in a dramatic decline of overall fish population" [29]. The food chain is also impacted by the pesticides and preservatives found in food waste. As marine life consumes food waste, they also consume the chemicals found in the waste. The bioaccumulation of such chemicals cycles up the food chain, and ultimately ends up in human diets [29]. As chemicals travel up the food chain, they become more and more concentrated and dangerous. Thus both aquatic life and human life is affected by the chemicals found in food waste.

As nutrients from food waste are deposited into the ocean, they accumulate and ultimately result in eutrophication, which is where algal bloom is initiated from high nutrient levels in water (Figure 2). Algal blooms disrupt the entire ecosystem by using up all of the oxygen in the water, blocking sunlight, and producing harmful toxins [29].

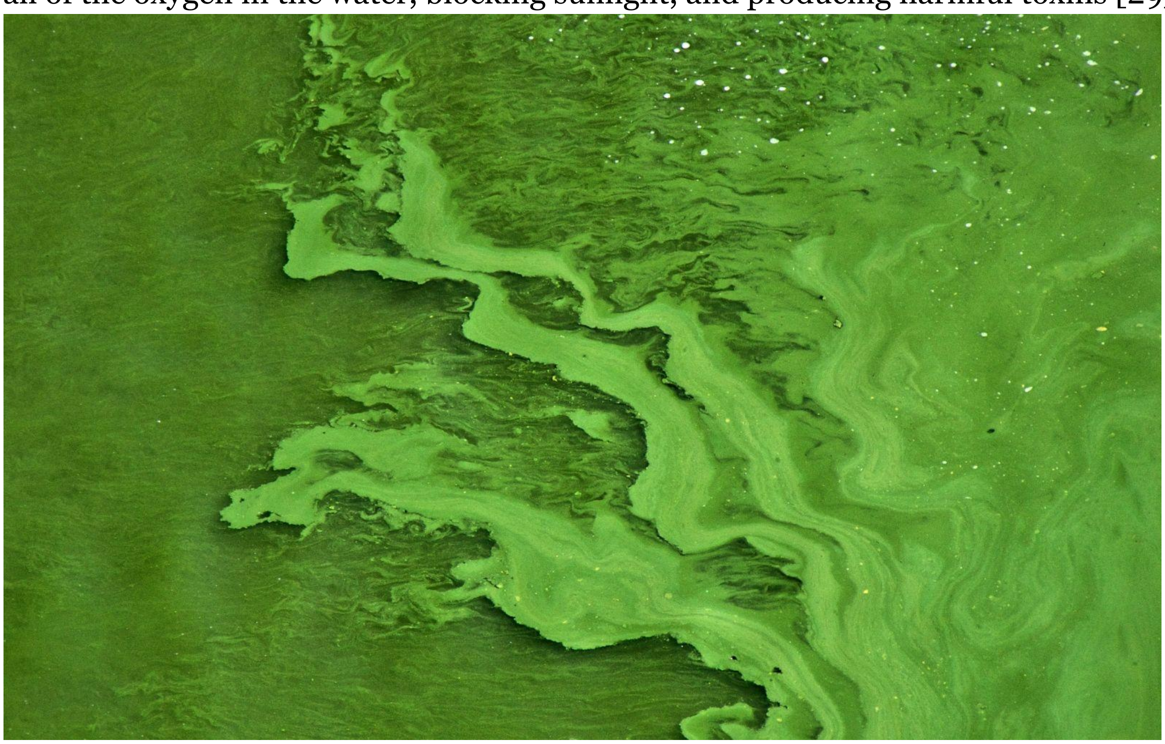

Figure 2. Algal Bloom in the Ocean (Photo by Mihály Köles on Unsplash).

Low oxygen levels can ultimately kill fish and seagrasses, coral reefs, and mangrove forests that are essential to fish habitats [30]. The blockage of sunlight prevents photosynthesizing plants from undergoing their necessary processes, reducing growth and causing die offs [29].

Eventually, the excessive algae begins to decompose, resulting in the production of large amounts of carbon dioxide. This lowers the pH of the ocean (increasing acidification), which slows the growth of many fish and prevents necessary shell formation in shellfish [31]. The release of carbon dioxide and other greenhouse gases can also cause mass mortalities of marine life and a loss of biodiversity [30]. Ultimately this affects humans once again, as the death of marine animals means a reduced catch for fisheries. Subsequently, the seafood they are able to provide the human population is reduced, and prices of seafood are increased [31].

The increased food waste caused by COVID-19 can cause a series of harmful effects, for both marine animals and humans. From disruption of predator and prey balance to eutrophication, food waste can be detrimental to aquatic ecosystems. With proper protocols, these issues can be addressed, but it is still important to understand how COVID-19 has increased food waste, and what this increased food waste can mean for aquatic life.

Conclusion and Future Directions

Current Developments. Reusable PPE eases the extreme amounts of mishandled disposable PPE that ends up in the ocean. Reusable masks could reduce waste during the pandemic by up to 95%, and the use of reusable face-shields with single-use filters could reduce waste by around 60% [7]. Additionally, improving the gas emissions of incinerators through new technologies must be implemented in all countries. This includes the use of biodegradable manufacturing of medical supplies that does not contain the toxic chemicals typically seen when incinerated. One such example is bioplastics [3]. Another way we have learned to control climate change is in regards to food waste. With an increase in the use of food banks during the pandemic, we can utilize the food that would otherwise be discarded. Farmers have begun to sell or donate their products to food banks in response [28].

Future Developments. There is much research and development that must be done in order to effectively combat the changes in our marine environments following the pandemic. We need to develop alternative reusing and recycling technologies in order to minimize our total amount of waste, specifically medical waste (Figure 3). Furthermore, we need to continue to investigate the use of green materials in the manufacturing of PPE.

Figure 3. Eco-friendly techniques for hospital solid waste management [7].

We must also develop new methods for the removal of microfibers and microplastics already present in the environment; new techniques are currently being developed to improve MP/MF breakdown. We also must monitor the levels of MPs in marine environments to gauge how they are changing from the pandemic, in order to inform legislative interventions [7]. We must conduct risk assessments in order to better understand the consequences of differing levels of MPs on marine organisms and ecosystems, and on various aspects of human organ functioning [7]. We should look comprehensively at other perspectives, such as biomedical or environmental, in order to manage ocean pollution [7].

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Chapter 4
Air Pollution

Chloe Heath and Rushil Vasant

Greenhouse Gases and Climate Change

With busy city streets becoming eerily desolate and passenger traffic reaching a near standstill, COVID-19 lockdowns caused significant declines in air pollutants and greenhouse gas emissions globally. Harmful air pollutants include particulate matter (PM), ozone, carbon monoxide, sulfur dioxide, and nitrogen dioxide. While short-term exposure to these pollutants increases the risk of respiratory conditions, long-term effects can involve lung cancer, heart disease, and stroke. Approximately seven million people worldwide die annually from air pollution, from which 1 in 5 deaths can be tied to fossil fuel (oil, natural gas, and coal) air pollution [1; 2].

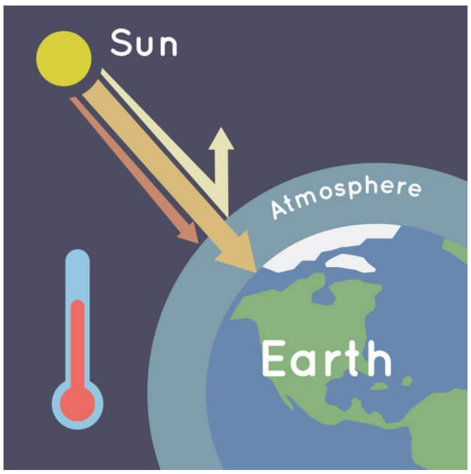

Figure 1. The Greenhouse Effect [4].

Major greenhouse gasses, on the other hand, include carbon dioxide (CO_2), methane, and nitrous oxide. Through the greenhouse effect (Figure 1), these gases trap the Sun's heat in the Earth's atmosphere and cause global temperatures to rise [3]. As the name suggests, the process operates much like a greenhouse used to cultivate plants. In the daytime, sunlight enters Earth's atmosphere and warms the planet's surface. As the surface cools at night, this heat is released back into the air and a portion of it is trapped inside the atmosphere by greenhouse gasses. Though the greenhouse effect is critical to keep our planet warm, human activity is intensifying this process through the emission of excess greenhouse gases. These emissions can trap additional heat inside the atmosphere and warm the planet beyond its natural state. Global warming is leading to long-term changes in temperatures and weather patterns (climate change) through sea level rise, ocean warming, glacier and ice sheet melting, flooding, droughts, and wildfires, for example.

The dramatic increase in global greenhouse gasses and air pollutants over the last century can be attributed to the production, transport, and burning of fossil fuels for transportation, electricity, and heat [5]. Fossil fuel burning has seen a substantial rise since the industrial era, primarily affecting the atmospheric concentration of CO_2. Although CO_2 emissions increased by approximately 50% since 1750, global emissions tanked by their largest historical drop in 2020 [6; 7]. This decrease—about double Japan's annual emissions—was largely linked to drastic reductions in energy demand and transportation activity compared to 2019 averages [7; 8]. By nation, the United States had the largest emissions reduction from 2019 (-12.9%), followed by India (-8%) and Europe (-7.7%). Surprisingly, China only took a -1.4% hit in 2020, but that can be explained by its quicker economic recovery in the face of the pandemic [6]. Comparatively, a higher incidence of COVID-19 outbreaks in the U.S. that year prolonged its economic turnaround and drove further emission declines.

Except for ozone levels, all other greenhouse gasses and air pollutants showed steep drops as well. Combined satellite and air quality station measurements from 34 countries between January and May 2020 reveal significant declines in PM (-31%) and nitrogen dioxide (-60%) [9]. These are notable drops as both pollutants can induce or aggravate respiratory diseases and lead to death. Environmentally, the organic and metal compounds present in PM can harm ecosystems through the uptake of deposits by plants or the accumulation in water sources leading to contamination [10]. High levels of nitrogen dioxide can also reduce crop growth and yield. Nevertheless, sulfur dioxide and carbon monoxide levels were lower in 2020 compared to the 2015-2019 global averages [11]. However, ozone concentrations exhibited variable patterns regionally, from no significant change to marginal increases like in Europe and intense spikes in both East Asia (+25%) and South America (+30%) [11]. On average, ozone levels increased globally by 4% during early lockdown months [9]. These unexpected rises point to the nonlinear relationship between nitrogen oxides, particularly nitrogen dioxide, and ozone. In abundance, nitrogen dioxide reacts with atmospheric ozone and removes it from the air like a sponge [12]. However, since nitrogen dioxide concentrations plummeted globally during lockdown measures, ozone levels rose. Though ozone is a vital part of Earth's atmosphere because it shields us from the Sun's harmful ultraviolet light, ground-level ozone can reduce lung function, irritate the respiratory system, and increase the risk of lung infection [13]. Among several downstream effects on biodiversity and wildlife, ozone can decrease plant growth, vitality, and photosynthesis—an essential process that produces the oxygen we breathe. Since higher ozone levels have been associated with elevated temperatures, ozone effects will intensify if the planet continues to warm [14].

Momentary improvements in ambient air quality amid COVID-19 were observed in two of the most polluted countries worldwide: India and China. While the majority of India's air pollution can be linked to construction dust and waste burning, China's pollution is largely attributable to its strong reliance on coal-fired power plants to sustain energy demands. With lockdowns slowing down both nations' residential, power, and industrial sectors, immediate air pollutant declines were observed. Among 16 Indian cities during lockdown, particulate matter 2.5 and 10 micrometers or less in diameter, $PM_{2.5}$ and PM_{10}, respectively, had 30-50% lower average Air Quality Index (AQI)[1] values compared to 2017–2019. With human hair being 50-70 micrometers in diameter, these particulates are quite small [10]. Nevertheless, a similar reduction was found for carbon monoxide, while a 40-60% decrease in AQI was recorded for nitrogen dioxide, indicating healthier, cleaner air [15]. As for China, the average AQI among 95 cities under lockdown decreased by 19.84 points relative to 324 non-locked-down cities [16]. With China's average AQI at a staggering 109.6 points in 2020 and an AQI value of 0-50 indicating good air quality, a drop of roughly 20 points is noteworthy [17]. Furthermore, among nine of the locked-down-cities hit hardest by COVID-19 (Huanggang, Ezhou, Wuhan, Jingzhou, Xiaogan, Jingmen, Huangshi, Xiangyang, Yichang), concentrations of PM_{10} and nitrogen dioxide fell significantly (Figure 2) [18].

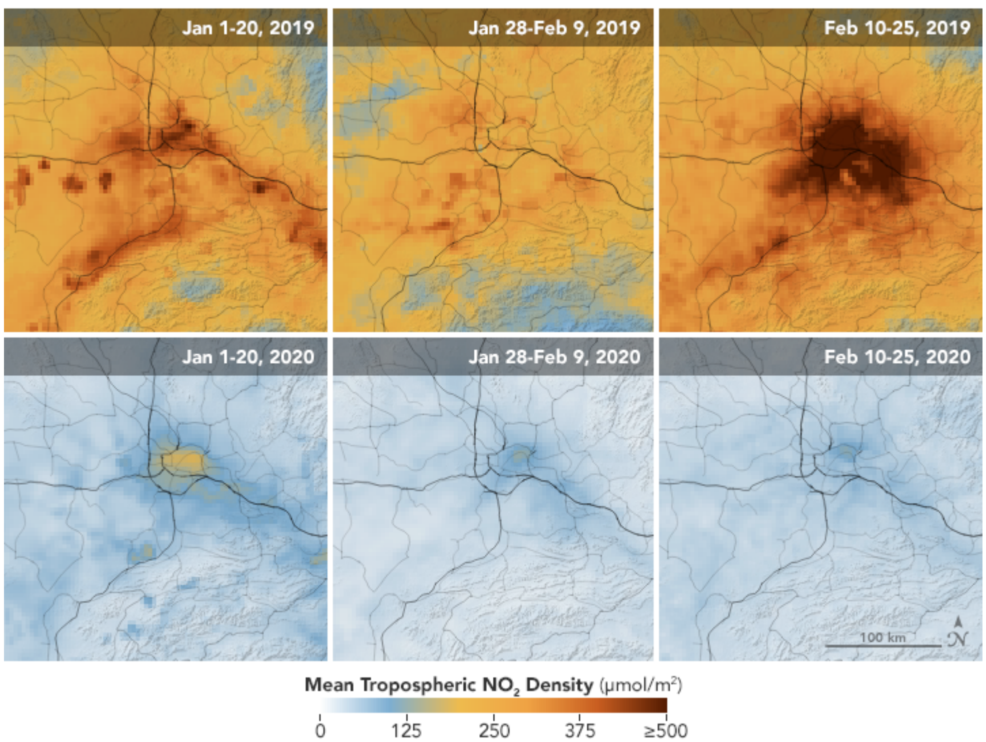

Figure 2. Nitrogen dioxide (NO_2) levels in Wuhan, China, from 2019-2020 [19].

Though polluted countries like India and China experienced sudden yet dramatic improvements in air quality, these benefits were relatively short-lived. Air pollution began rebounding to pre-pandemic levels as lockdown measures were gradually lifted and routine fossil fuel activities resumed. In China, nitrogen dioxide concentrations in

[1] Scale ranging from 0-500 that is used as a measure for air quality. Lower values indicate better air quality. Each air pollutant has its own AQI sub-index value, which are averaged together for an overall AQI.

Beijing reached pre-pandemic levels within a year after lockdown, but Chongqing nearly doubled its pre-pandemic concentration by 2021 [20]. As for particulate matter, PM_{10} increased at a 44% rate by September 2021 in three Chinese cities most severely affected by COVID-19 [19]. Similar air pollution rebounding was observed for most countries post-lockdown, and this pattern holds for greenhouse gas emissions also, which reached a new record high in 2021 (Figure 3). In particular, while global CO_2 emissions were curbed in 2020, they rose back to pre-pandemic concentrations and reached their highest-ever level in 2021 at 80 trillion pounds of CO_2. This marked a 4.4 trillion pound CO_2 increase from 2020, offsetting the emission decline caused by the pandemic [21]. Such a rise was induced by a high dependence on coal to satisfy the growing energy demand of the post-lockdown world. In fact, coal burning was responsible for more than 40% of the 4.4 trillion pound CO_2 increase in 2021 [22]. Coal became the favored fossil fuel for energy production during this period due to its affordability over natural gas.

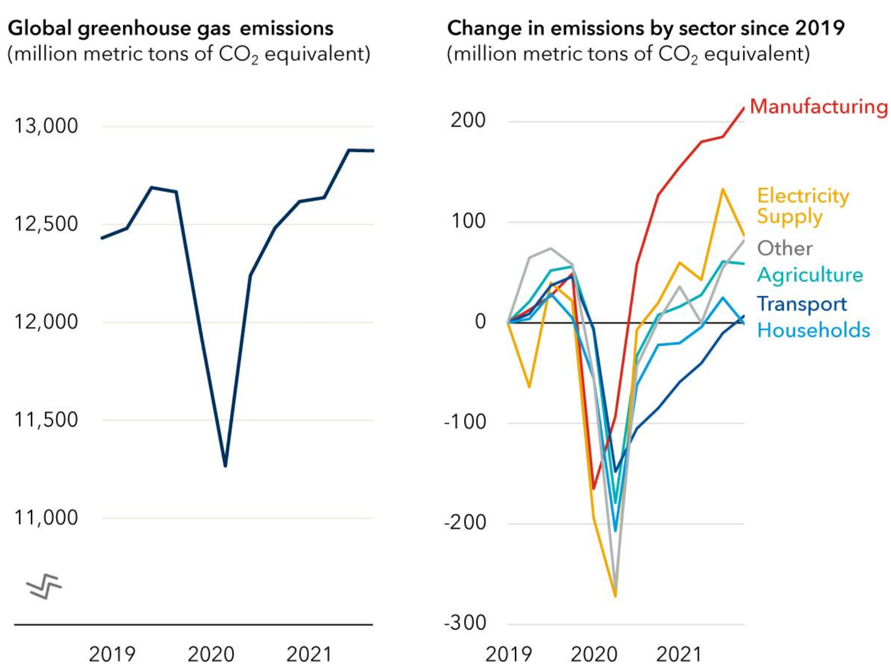

Figure 3. Changes in global greenhouse gas emissions from 2019-2021 [23].

Although medical waste and PPE waste were not the root causes of rebounding greenhouse gas emissions and air pollutant levels, they were certainly notable factors that call for a closer examination. Upwards of 1.8 trillion pounds of greenhouse gasses are produced annually from the production and incineration of plastics, which constitute over half of PPE [24]. Estimates reveal that 76 million examination gloves, 1.6 million safety goggles, and 89 million medical masks were needed monthly to support the COVID-19 response, of which the latter two contain plastic components [24]. With

PPE being increasingly used during and following the pandemic, the use of plastics within these materials exacerbated plastic pollution at the expense of public health: almost 18 billion pounds of pandemic-related plastic waste was produced globally, the majority of which was from medical waste [25]. At least 56 million pounds of that harmful waste ended up in our oceans, ultimately affecting air quality and climate change. These plastics can break down into lightweight microplastics and be blown into the atmosphere or be ingested by marine organisms like phytoplankton, which produce oxygen through photosynthesis. Microplastic ingestion can inhibit phytoplankton photosynthesis and growth, threatening the source of about half of Earth's oxygen production [26]. Of course, microplastics can kill marine life as well due to their toxicity, leading to further environmental implications. Additionally, while airborne microplastics can pollute the air and enter our lungs to likely induce respiratory conditions or exacerbate existing ones, they can also affect cloud formation. Clouds form when water vapor condenses on fine particles or "seeds" in the air like dust. Studies have revealed that microplastics can seed cloud droplets and thus cause potential changes in rainfall patterns, temperature, and possibly climate change [27]. The impact of microplastics on global warming remains uncertain.

Undoubtedly, the contribution of medical waste and PPE waste toward greenhouse gas emissions and air pollutant levels brings the practicality of plastic-based PPE into question. Plastic-based PPE starts off as fossil fuels and prompts greenhouse gas emissions at every stage of the life cycle, from fossil fuel extraction and transportation to PPE production and use, and finally the disposal process. The equipment with the highest environmental footprints are gowns (2 pound CO_2eq)[2], face shields (0.5 pound CO_2eq), and cup-shaped filtering facepiece respirators (0.28 pound CO_2eq) [28]. Unsurprisingly, the highest used PPE during the pandemic were face masks. Surgical and cloth N95 masks, respectively, generate 0.13 pounds CO_2eq/single-use (with transportation) and 0.08 pounds CO_2eq/usage (with washing) [29]. The production and disposal of these PPE make up the majority of their greenhouse gas footprints, the latter of which can also pollute the air and bodies of water with toxic compounds via landfills and incineration. Collectively, the environmental footprint of PPE is quite significant. The combined carbon footprint of all PPE provided to healthcare centers in England between February-August 2020 was found to be nearly 235 million pounds CO_2eq—26,662 times higher than the average person's six-month carbon footprint [28]. The highest volume items were gloves, followed by aprons and face shields.

[2] A carbon dioxide equivalent (CO_2eq) is a standard unit for measuring carbon footprints.

Changes in Human Activity

With the earliest U.S. cases of COVID-19 appearing in the San Francisco Bay Area, California became the first state to declare a statewide stay-at-home order which mandated all residents to leave their homes only to perform essential activities such as work that could not be performed from home or shop for essential goods [30]. Accompanying this order was a feeling of desolation across cities once bustling with traffic and pedestrian activity. As the number of COVID-19 cases began to skyrocket, 42 more states followed in California’s footsteps and instilled their own stay-at-home orders. Ultimately, these orders affected Americans' use and choice of transportation.

The U.S. Bureau of Transportation documented significant changes in American mobility throughout the pandemic. For example, the stay-at-home population skyrocketed at the onset of the pandemic to over 100 million Americans with notable drops in April and December 2020. Concurrently, the number of Californians making 3-5 mile trips dipped to around 8-10 million from April 2020 to January 2021, compared to 18-26 million during the same period in 2019. Additionally, the number of Californians making trips greater than 500 miles from October to December 26, 2020, remained below 100,000 compared to the same period in 2019, where the range was 90,000-130,000 [31]. This data indicates that Americans traveled short and long distances less frequently during the pandemic. As one might expect, with a drastic decline in human activity, road transportation use and commercial flight activity dropped by nearly 50% and 75%, respectively, relative to their 2019 averages by early 2020 [32]. Figure 4 illustrates how Bay Area Rapid Transit (BART) train ridership dropped dramatically as the pandemic progressed, going from nearly 400,000 riders exiting per weekday in January to approximately 25,000 riders exiting per weekday in April 2020. Interestingly, ridership numbers have yet to fully recover with numbers hovering around 150,000 riders exiting per weekday as of 2023 [33]. In addition to the stay-at-home order implemented in California, the fear surrounding COVID-19 contributed to low ridership numbers. Three particular factors made public transportation undesirable during this time: many people were confined to limited space, the inability to identify sick passengers, and there were multiple surfaces capable of transmitting germs. This ultimately led to the United Kingdom advising citizens to consider all other forms of transport before using public transportation [34]. Similar recommendations and the fear of contracting COVID-19 exacerbated low numbers.

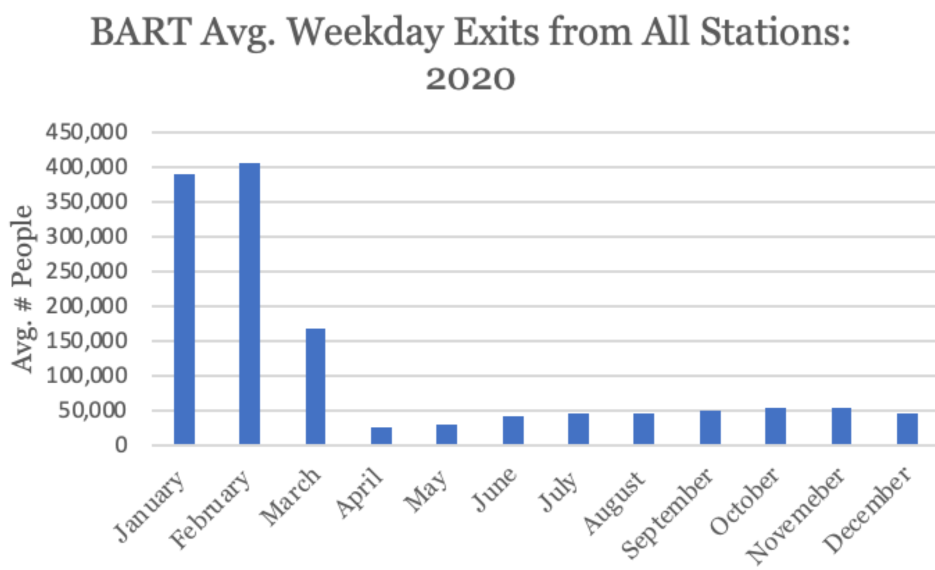

Figure 4. Changes in ridership of BART trains during 2020 [32].

With drops in public transportation ridership came spikes in bicycle and automobile purchases. According to the U.S. Bureau of Economic Analysis, Americans spent nearly 1 billion dollars more on bicycles and bicycle accessories in 2020 compared to 2019, and this trend continued into 2021 [35]. Biking served both as a means of transportation for those who normally rely on public transportation and as an enjoyable outlet during a time of isolation. Cities adapted to the increase in bicycle use, implementing pop-up bike lanes or street closures on the weekends. European cities whose infrastructure promotes biking and walking, such as Brussels, Berlin, and Paris, invested in 15-50 miles of pop-up bike lanes for their citizens [36]. Additionally, in New York City, bike-sharing dropped by 71% compared to a 91% drop in subway use, showing that bike-sharing can be a much more resilient system than the subway. This could be because biking allows for users to ride on their own schedule and minimizes direct contact between individuals. However, some New Yorkers preferred cars over bikes, with car registration in New York jumping by 37% in 2020. This caused a large influx of cars on the road and impacted how walkers and bikers were able to navigate through the city [37].

Although no form of transportation is perfect, biking greatly reduces greenhouse gas emissions and noise pollution while also decongesting roads. Those who choose to make one less car trip and one more bike trip per day decrease their CO_2 emissions by 67% [38]. Like any other form of transportation, there is an initial energetic and environmental cost to building bikes. It takes an estimated 211 lbs of CO_2 to produce a traditional bike and 295 lbs of CO_2 to build an electric bike (E-bike). This is mostly due to the extraction of raw materials and the use of heavy machinery during production [39]. However, once a bike is produced and sold, its carbon footprint is nearly zero.

Biking produces 21 g of CO_2 per mile compared to 503 g per mile for a car. Although bikes do not directly produce CO_2 the way cars do, they do require energy from the rider that must be replenished by food [40]. Food consumption ultimately impacts air pollution because of methane emitted by cows, for example. Overall, biking is an environmentally friendly investment, as it is estimated that someone eating the average American diet would need to ride approximately 430 miles to offset the initial carbon footprint from bike production [41]. With the average American bike commute being just over 5 miles, it would take just under 3 months for an individual's bike purchase to be nearly carbon neutral [42].

E-bikes offer one of the best alternatives to private transportation. Unlike forms of public transportation like trains and buses, which are ubiquitous in large cities but less common in rural areas, E-bikes provide transportation for an individual who desires to go short, intermediate, or long distances. Using E-bikes as an alternative to cars for intermediate-distance travel is extremely impactful to CO_2 emissions. In England, one-fifth of the journeys made by cars are between 8-16 miles. While this distance is often too far to walk or bike with a regular bicycle, E-bikes can make this journey with ease. Thus, replacing car transportation with E-bike transportation for distances in this range can be quite beneficial. E-bikes are estimated to have the capacity to reduce CO_2 emissions by 53.8 billion pounds in England alone [43].

Because of drastic changes in human activity in 2020, some refer to it as "the year the Earth could breathe." However, changes in mobility and human activity had mixed effects on the environment, especially regarding air pollution. While we may not yet know the long-term environmental impacts of 2020, we can break down each change in human activity and analyze it from an environmental perspective.

As aforementioned, a greenhouse gas absorbs and emits thermal infrared radiation, resulting in heat being trapped in Earth's atmosphere. While greenhouse gasses are necessary to keep Earth warm and hospitable, they are also responsible for the extreme global warming that has taken place over the past 200 years. How do greenhouse gases relate to COVID-19? Changes in human activity greatly affected the transportation sector, which is responsible for one-third of all greenhouse gas emissions in the U.S., because CO_2 is emitted from common forms of transportation [44]. Global CO_2 emissions in the first quarter of 2020 declined by 5% compared to the first quarter of 2019, and CO_2 reduction was felt strongest in places that were hit hardest by COVID-19: China, the European Union, and the United States. Additionally, changes in gasoline demand demonstrate the effects of COVID-19 on transportation with global demand being lowered by 1700 barrels per day during the first quarter of 2020 compared to the same period in 2019 [45]. Environmentally, the decrease in road vehicle and aircraft use was favorable. But what about changes in public transportation? Although most forms of public transportation, such as trains and buses, run predominantly on fossil fuels and are not zero emission, public transportation plays a substantial role in reducing greenhouse gas emissions. Public transportation produces much less emissions per rider than a car, resulting in cleaner air [46]. Accordingly, one would hope that public transportation use recovered stronger than ever after the pandemic, but ridership numbers are still down in certain locations. This stunted recovery is likely a result of many jobs becoming hybrid or fully remote, resulting in fewer people commuting to work. Changes to public transportation have also been implemented to make it more appealing post-pandemic [47]. Public transit services are more reliant on digital ticketing and have had growing interest in changing train designs to decrease person-to-person contact.

Changes in mobility also resulted in changes in consumerism. With few shops open, people began to look towards e-commerce for both essential and non-essential goods. From 2019 to 2020, e-commerce boomed, growing by 32% in the U.S. alone [48]. The pandemic accelerated grocery e-commerce by years in the span of a few months. Online shopping increased for non-essential goods with recreational spending increasing by 18% [49]. E-commerce became a haven for people to find essential goods and served as a temporary cure for quarantine boredom. But what are the environmental costs of online shopping? While one might intuitively think that online shopping is better for the environment because it saves a trip to the store, the environmental implications of online shopping are still relevant. Strikingly, online shopping uses 4.8 times the amount of packaging as offline shopping. With online shopping growing at its current rate and how much packaging is used per purchase, waste will increase by an additional 10% in the next 10 years [50]. Although some of this waste is recycled, much of it will end up in landfills or polluting waterways.

Ultimately, COVID-19 resulted in unprecedented changes in human activity. While changes in human mobility resulted in fewer greenhouse gas emissions during 2020, other changes, such as increases in online shopping and decreases in public transportation use, caused greater waste production and pollution. COVID-19 elucidated weaknesses in common forms of public transportation, such as trains and buses, while also bolstering the strength of bike ridesharing programs and their resilience. Biking spiked as a form of transportation and leisure, and cities all around the world made steps toward supporting this mode of transportation.

Public Health Concerns

For many people, respiratory illnesses are part of their everyday life. More than 34 million Americans live with chronic respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD), which includes chronic bronchitis and emphysema—a lung disease that causes shortness of breath [51]. COPD is characterized by an inflammatory response in the airway due to PM, while asthma is often triggered by allergens, exercise, or a respiratory infection. These diseases result in severe coughing, phlegm production, shortness of breath, and chest pain [52]. Additionally, those with COPD are at greater risk of developing heart disease and lung cancer [53]. To participate in everyday activities, many individuals with COPD and asthma rely on medication, inhalers, and supplemental oxygen.

Poor indoor and outdoor air quality are major contributors to the exacerbation of asthma and COPD with different parts of the world posing distinct risk factors (Figure 5). Whether it is poor air quality, poor indoor ventilation, exposure to asbestos, aerosol usage, or exposure to tobacco products, there are myriad ways by which chronic lung illnesses are influenced by the environment. For example, a study in Madrid found that indoor air quality decreased because of poor ventilation and increased aerosol use. This resulted in a 12% increase in $PM_{2.5}$ concentration, potentially exasperating respiratory illnesses [54]. As previously mentioned, the spread of COVID-19 and the establishment of stay-at-home mandates resulted in a dramatic dip in transportation activity, causing a decrease in outdoor air pollutants like PM, CO_2, and nitrogen dioxide. In contrast, stay-at-home orders confined individuals to their homes for longer durations, potentially exposing more people to poor indoor air quality.

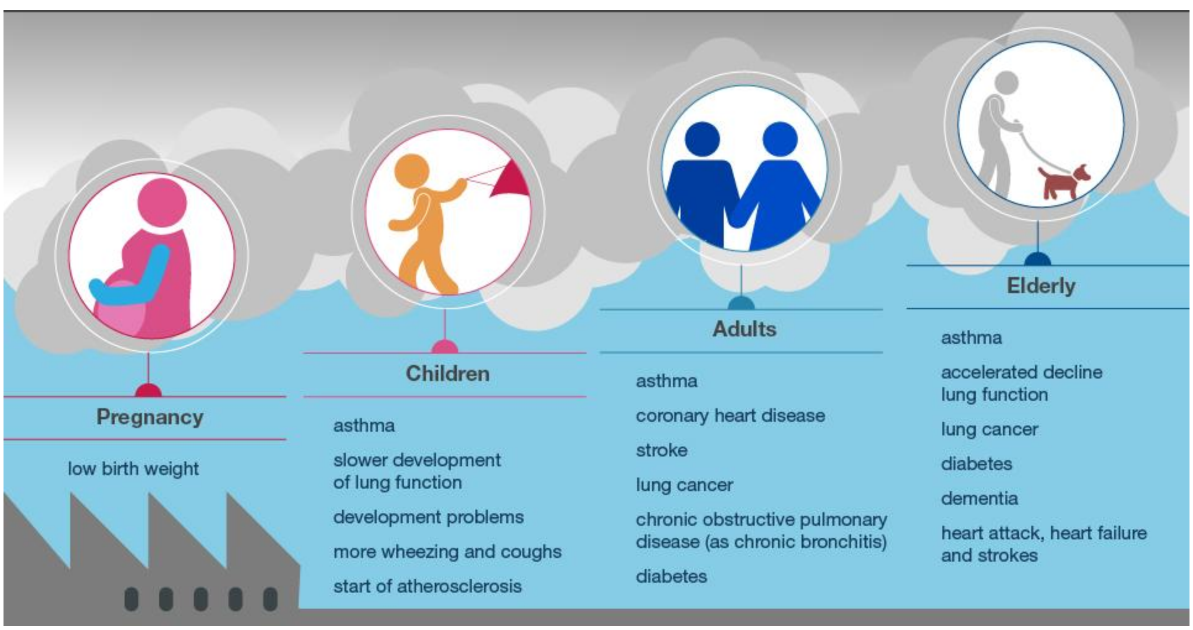

Figure 5. Health effects of air pollution across a person's lifetime [55].

Ironically, although COVID-19 is an infectious disease that attacks the lungs, emergency room admissions for pediatric respiratory diseases were down during the pandemic compared to the 2016-2017 period [56]. Similarly, another study looked at how non-pharmaceutical interventions affected hospitalization for COPD, pneumonia, influenza, and asthma. This study spanned from February 2020 to July 2020 and compared findings from January 2016 to January 2020. The study found that the incidence of hospitalization due to COPD and asthma were 58% and 48%, respectively, compared to before January 2020 [57]. Besides the decrease in PM and other pollutants that are harmful to the respiratory tract, respiratory illness-associated hospital admissions decreased because of the nearly ubiquitous mask use. In fact, roughly 74% of Americans wore masks when leaving their home during the pandemic [58]. Although mask types vary, the most common are surgical masks and N95 masks, which can filter out 90% and 95% of PM, respectively [59]. Thus, Americans, and millions of other mask wearers around the world, were protecting themselves not only from COVID-19 but also from other respiratory illnesses like COPD.

Improving air quality and wearing masks are both ways to reduce contact with harmful air pollutants. Air pollutants have long been linked to an array of acute and chronic respiratory diseases and were relatively recently associated with a higher COVID-19 death rate. In particular, PM_{10} and $PM_{2.5}$ can travel deep into the respiratory tract once inhaled and reach the lungs, causing lung irritation, reduced lung function, and potentially chronic bronchitis [60]. Air pollution is responsible for approximately 25%, 29%, and 43% of global annual deaths caused by heart disease, lung cancer, and COPD, respectively [61]. With COVID-19 lockdowns causing declines in PM concentrations across polluted countries like India and China due to reduced residential, power, and industrial sector activities, the likelihood of developing severe respiratory conditions other than COVID-19 reduced. Evidently, a cohort study in Hong Kong found that there were reduced average daily hospital admissions for COPD (-36%), asthma (-37%), and non-COVID pneumonia (-12%) during the pandemic compared to the 2017-2019 period [62]. These reductions in hospitalization were tied to improved air quality and increased mask use. Data also reveals evidence of increased asthma-associated mortality in China because of short-term exposure to ambient PM [63]. The relationship between less air pollution and reduced respiratory disease prevalence points to a daunting post-pandemic future as global greenhouse gas emissions continue to rise and air quality worsens. The groups most vulnerable to air pollution health effects include children, pregnant women, the elderly, and those with pre-existing cardiovascular disease and/or respiratory disease.

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Chapter 5
Resource Depletion

Alisha Burch and Shivali Mrityunjay Hiremath

Introduction

There are far too many factors needed to run the world that took a beating from how and when the pandemic started. We will establish a base amount of knowledge that allows our readers to understand how widespread the effects of the pandemic have been over its course. No matter where you go, you will always see the results of the pandemic and how our governments handled the situation. This chapter aims primarily to inform its readers of the various effects the pandemic has had over its course, beginning in late 2019. The results, even as it hasn't completely ended yet, are to be discussed in as much depth as possible. However, bear in mind that the effects discussed here may not even begin to consider all of the possible effects that took form in the last few years.

The Over-Dependency Problem

People need money, a roof over their heads, water, food and items left for self-care and personal hygiene, and it so happened to be that groceries were one of the most deeply affected human needs by the pandemic. Running out of daily essentials meant that people were more willing to pay for more expensive products. Toilet paper is perhaps the most well known of the previously depleted materials, but goods such as spiral hams, hair dye, baking yeast etc., had significant disruptions in their supply chain causing a spike in their prices. An inflation rate of 1.7% jumped to 5.3% in the matter of months in 2020 [1]. With the rise in inflation, there were restocking issues and scarcities which pushed retailers to sell to customers products at higher prices. The temporary product shortages went from being temporary to permanent and soon after these permanent stockouts increased sharply, discontinuing about 20% of products [1]. These disruptions were easy for consumers to observe due to the empty store shelves. As a result, consumers feared not being able to obtain resources and began to overbuy. Currently, these shortages have begun to dissipate but the pressure to increase prices from the shortages has not.

What exactly triggered the rise of inflation rates at this particular time of 2020? Studies have shown that this specific period of rise in inflation had three main causal factors: one, major and inconsistent changes in the usage of energy; two, work orders running behind schedule because everyone was forced to work virtually; and three, changes in the demand for auto-related goods and services. The lockdown began a chain of events that ultimately led up to where we are today: inflation rates still high; labor forces in developing countries continuing to feel rising pressure from their multinational company employers; and lower economic growth rates, to name a few.

Our dependency on energy within people's households shifted energy usage to such extents that we never knew were even possible. Instead of using air conditioning services from workplaces, we started using them at home - which used a marginally larger amount of power than in the workplace environment. And to have millions and millions of individual households resort to their own air conditioning services meant that a much larger amount of energy was in demand. The energy demand from households in developed countries, like the United States and the United Kingdom, shifted from their previous dependencies on the healthcare, technology and retail industries (healthcare saw another spike in energy consumption which will be addressed later in this chapter) to industries including, but not limited to, automobiles, electronics, energy, agriculture and education [2].

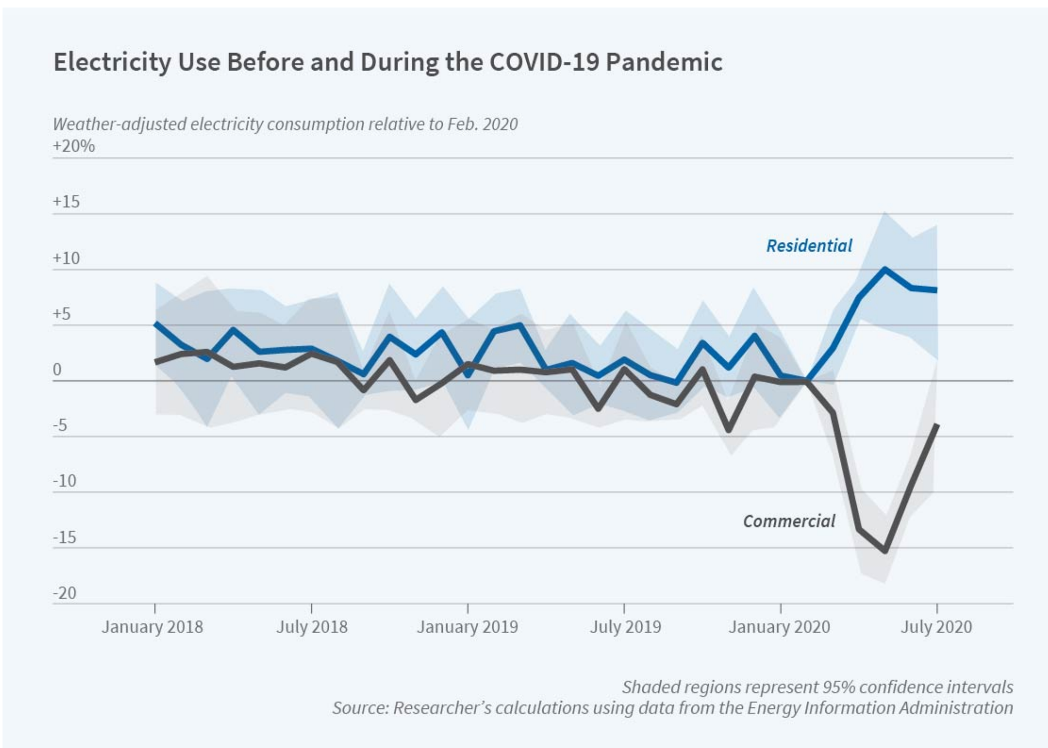

Figure 1: Usage of electricity by residential and commercial sectors before and during the pandemic [3].

As previously mentioned and seen in the data above, the difference between residential and commercial energy usages see some really abrupt changes. However, the amount that commercial energy consumption reduces is slightly higher than that of residential energy consumption. This change has a logic that explains it that takes a path that we did not predict in the short run.

With all the immediate effects brought to attention earlier in this section, there came a recession period that people were as surprised as they were when they learnt of COVID-19 cases all over the world. People being sent home to work virtually meant that the production line for physical items to be made slowed down drastically. While this explains the toilet paper shortage, it also explains how a large percentage of the labor force had to be let go by their employers in order to keep the company afloat in the market. More than 14 million people were laid off between February and May - this was an almost 250% rise in the pre-pandemic unemployment number [4]. Employers from restaurants and healthcare facilities were the most affected, but in two completely different ways. The healthcare industry is a separate section that we decided to address in this chapter. The unemployment rate rose from an approximate average of 8% to nearly 24% in India, in the matter of one week in May, 2020 [4]. India, being a developing country, would have faced changes to the economy to this extent simply because it is a developing country.

Restaurant employees and their employers suffered seriously, firstly, because they were often small businesses that only made so much profit from customer tippings, primarily. People staying at home to eat meant that the restaurant would begin to face losses in their finances to a point where they would no longer be able to keep their waiters and chefs employed. People who would have had job security working at a restaurant for long periods of time suddenly found themselves without a source of income. As a result, a lot of these small, family owned businesses, like restaurants and salons, went bankrupt and eventually stopped providing their services.

Changes such as these, and on a large scale, had resulted in a stunt in the growth of the US economy, and most other economies all over the world.

Import and Export during the Pandemic

Another issue that arose from COVID-19 was the impact on importing goods. The pandemic disrupted shipping by air and sea. This caused the cancellations in sailings and cargo flights, along with port delays and container shortages. In the beginning of 2020 the imports of the U.S. Maritime containers declined by 7% [3]. There was also a slowdown in manufacturing in China which caused shipping firms to cancel scheduled deliveries. This pushed the large shipping alliances to cancel more than 1,000 voyages during the beginning of 2020 [3]. Due to high customer demand, the merchandise trade began to recover but this was still affecting the maritime freight sector and capacity shortages. Shipping firms struggled to recover their previous capacity. These firms were operating at full extent which resulted in a depletion of the shipping container inventory. When the pandemic first began, the production and demand for containers dropped. Since the demand suddenly increased after lockdown, container manufacturing shifted to Asia causing a rise in costs for U.S. importers.

In addition, many port workers were infected with the virus which decreased the amount of cargo moved onto ships. This also coordinated with the updated health policies within the area. As mentioned before, the labor shortage impacted the global supply chain. Another issue was that travel restrictions and quarantine procedures reduced labor mobility. It was estimated that 800,000 seafarers could not leave their vessels due to quarantine procedures. Other factors to take into consideration when it comes to the workers is the expenses, which increase by 6.2% [3]. Certain costs needed to be covered for workers such as hardship compensation and COVID-19 testing expenses.

When it came to air cargo, there was a decrease in capacity in the cargo holds on passenger aircrafts. This was an effect of all the canceled flights. In 2020 the global Cargo Tonne Kilometers (CTK) reached its largest decline since 1990. When countries announced the travel restrictions, the volume of U.S. travelers were reduced from 78.7 million to 3.0 million [2]. Some airlines even went as far as removing the interior of passenger aircrafts to convert them to cargo aircrafts.

Due to all the shipping disruptions, resources became scarce and increased in price. COVID-19 impact on global transportation is a huge contribution to scarcity and higher prices. For instance, the cost of shipping one kilogram of air freight from Hong Kong to North America increased by 102 % [2].

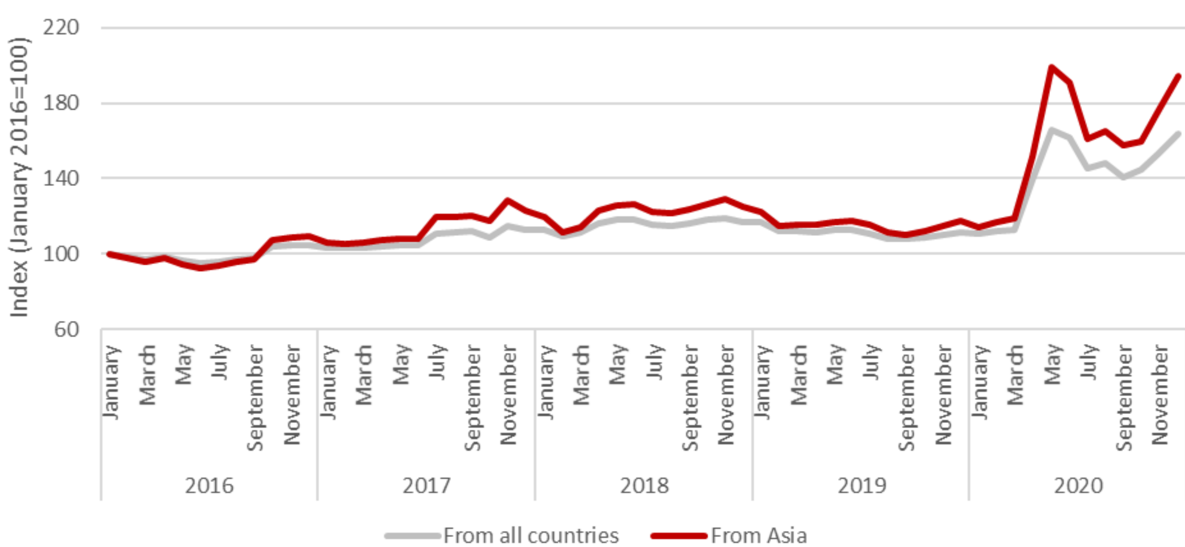

Figure 2: U.S. inbound air freight price index 2016-20 [2].

Infrastructural Effects on the Environment

Construction workers need resources from the environment to build what people require everyday. But what if the people were suddenly forced to stay at home, including those construction workers? The lockdown brought everyone back home, meaning that there were far less people using public or private forms of transportation outside to get in and around town. Less people outside meant less people requiring new construction and that, in turn, meant less construction projects. And less construction meant reduced reliance on environmental resources to build what people would have normally needed in their day-to-day lives.

Outdoor transportation almost came to a complete halt, and with it came a lowered amount of carbon emissions during this time (Chapter 4). Staying at home required the use of more home resources, such as electricity and natural gas. Turning on the heater during winter and the air conditioning during the summer meant that people would leave them on for as long as they were at home - which at the time, was the entire day. Home use of energy is less efficient than most office and business use because 35% of it is wasted.

Healthcare Resources

As previously mentioned, the healthcare industry did indeed take a huge toll on its employees and their employers. Product shortages and the inability to import healthcare resources contributed to the depletion. The shortages in these materials led to a large increase in prices. The price of isopropyl alcohol increased more than 3 times its original price (per metric ton). Furthermore, care for one COVID-19 patient in intensive care requires at least 36 pairs of gloves, 14 gowns, and 3 pairs of goggles [3]. Chapter 2 describes the extensive need and use of PPE for medical workers. As the number of patients skyrocketed, the need for PPE strained resource availability.

During the pandemic, over 300 million respirator masks were needed in the U.S. but domestically there are only 35 million manufactured [3]. There was an increase in the need of ventilators and pharmaceuticals to treat respiratory diseases. Healthcare organizations faced the task of managing the healthcare supplies but also maintaining sustainability. If the issue is not addressed properly, the health of patients and workers were threatened. The absence of PPE can cause healthcare workers to get infected and disrupt the workforce. For example, the issues with healthcare supplies led to 15,000 healthcare workers in Spain becoming infected which impacted the treatment of the virus.[3]

Healthcare workers faced stress, anxiety, and long shifts [4]. Many healthcare workers traveled to new places so that they could aid overwhelmed clinical areas. This resulted in many staff members being put into the ICU setting despite lacking the proper training. The ability to train and supervise the clinical volunteers was difficult to achieve. Many professionals were forced to wear their personal PPE due to the PPE shortage. They also struggled to keep up with new procedures and knowledge introduced during the pandemic [4]. The ability to attend to ill patients continued to worsen due to the lack of sufficient resources and specific treatment. Many workers had to care for their own colleagues who had gotten sick and take on the pressure of comforting the dying patients who couldn't have families. This put a huge toll on workers emotionally while they had to ethically make the decisions on how to manage their ICU admissions. Also there was the sad reality that many other patients that did not suffer from COVID-19 were not able to receive their treatment due to the staff being forced to attend to only those with the virus. Healthcare workers were forced to isolate for months from their family because they feared transmitting the virus. This, along with working remotely brought a loneliness that attacked their mental health. Workers lost payments, and the training of medical students were put on pause which caused a lot of missed opportunities.

Home healthcare workers not only experienced a lack of PPE, they also experienced lack of support, even hostility, from patients. IThis caused many healthcare workers to abandon their post or refuse to care for COVID-19 patients. Healthcare workers were at risk of experiencing severe burnout caused from the increased work demands and trauma. These workers report months to years of chronic stress effects. The long term effects on their health has yet to be seen [4].

The pandemic also caused a shortage in insurance coverage in the United States. The pandemic brought a huge surge in unemployment which has caused many to lose their employee sponsored insurance. Even workers who still have their jobs have experienced a drop in coverage due to employers cutting their cost due to financial strain. The over reliance on insurance provided by the employer and the federal government's inability to put effort into educating the unemployed about their eligibility for insurance added complexity [5].

The US public health system failed to control the spread of the coronavirus due to its inability to make testing widely available early in the pandemic. The National guidance on controlling the pandemic was also inconsistent. Many states refused to follow the recommended procedures by abandoning the social distancing guidelines. Many Americans distrust the government and this has caused public health to be under sourced. In addition,there is no public health information system to manage the demand for resources to combat COVID-19. Without such a system, there is no way to know where to direct resources. This shows just how underprepared the U.S. is for the next pandemic [5].

The Indian Case Study

The country that most people have heard COVID-19 news about would probably be India during the second wave, the Omicron wave. Omicron happened all over the world, not just India, but the implications in India that we saw in news channels at the time of impact were way more drastic in India than most other countries. The second COVID-19 wave in India took place between 16th February and 31st May, 2021 and this section aims to run through the causes of this wave.

The second wave took form because of a new strain of the virus: severe acute respiratory syndrome was added to the list of COVID-19 symptoms, making it what we now refer to as SARS-CoV-2. While there were already variants of COVID-19 developing as the virus spread, the addition of a symptom of this severity exponentially increased the death toll through the period. There were many reports shown on local news channels about how nonchalant everyone was about the pandemic in general. The Indian government themselves had a difficult time organizing the people and creating proper rules and regulations to reduce the spread of it. The residents of India just didn't seem to care enough about the disease than they did about their livelihoods out in the workplace. They did not respect the mask-wearing policies, nor did they adhere to the lockdown restrictions placed by government officials.

One aspect to remember before antagonizing the country and its people, is that India is a developing country. A large portion of the population does not have access to technology that would allow them to work from home. Any kind of technology supplied to employees, especially in bigger corporations and firms, were strictly monitored and some companies even went so far as to not allow their employees take equipment home to work. The people became reluctant to stay home because otherwise, without the goods or services they provide on a daily basis or the technology to access at home, they lose any chances they had previously of making more money.

In terms of land area, India is an extremely small country housing an extremely large population. What usually happens in big, metropolitan cities is that everyone tends to cluster together and live in these few areas in and around the city such that the population density skyrockets. There are, however, a lot of rural areas all over India whose population densities are drastically lower. People began considering moving back to their rural, relatively isolated hometowns from the city center, where everyone lived tightly packed next to each other. The chances of spreading the virus rose with every traveling person between rural and urban areas.

Psychology through the Pandemic

Before the pandemic a total of 51.5 million people suffered from mental illness [6]. Due to COVID-19 there was an increase in anxiety and depression. The fear of death, isolation, financial issues, and other factors impacted forty percent of adults [6]. There was also a shortage of psychiatrists and other mental health professionals. Many U.S. counties lack a single psychiatrist. Since the mental health needs have grown with the pandemic, there are a lot of openings for training and hiring new mental health workers. Providing training costs a lot and the government funding may not be adequate enough to address it. The pandemic has also pushed mental health care online. It's able to extend help to underserved communities because some patients live in areas where there is no access to psychiatrists. Without support, many patients ended up in inpatient treatment when it became available [6].

Exploitation of Habitats and Ecosystems

COVID-19 is one of the many global pandemics that has been caused by urbanization and shifting into environmental apathy. Typically when it comes to the pandemic, the general public focuses on causes related to the immediate present: things like social distancing and improper testing. COVID-19 is one of the many global pandemics that has been spread, but a long term cause is by urbanization and shifting into environmental apathy destroying natural world interactions.

Initially, humans contracted diseases by moving into new ecological niches for agriculture. As we evolved, the domestication of animals also increased exposure to infectious illnesses.[7] As society developed, so did medical treatments but we have now regressed back to the early contraction of disease due to globalization. This leads us to settle in natural environments which increase contact with wildlife. Such interactions allow the disease to jump from one species to another. The chances of this occurring becomes more likely as humans destroy natural habitats and venture deeper into nature. Contact between humans and animals has led to new diseases like SARS [7].

Habitat destruction also fuels pandemics. Because of the pressure on biodiversity by agriculture expansion, logging, and infrastructure development, one third of diseases emerge. Their actions change species composition and benefit the spread of disease from animals such as bats, odorants, and birds. Increased disease exposure also correlates differently depending on certain factors. For instance those who work in agriculture are more likely to obtain a pathogen infection like malaria. This exposure is a result of deforestation from farming. This means the individuals lacking in the resources to treat the illness are the most susceptible to contracting it [7]. We tend to ignore the exploitation of natural resources but it is shown that doing this has an immediate impact. If we continue to destroy nature it will also destroy us.

Conclusion

Although the dilemmas of resource depletion previously mentioned were caused by the pandemic, society has been working to improve these conditions over time. For example, with resource depletion, the availability of goods recovered gradually and some even have returned to pre-pandemic levels. When it comes to shipping disruptions, the maritime shipping capacity has returned to 2019 levels. The port capacity and air freight, however, continue to be strained. Ocean carriers are ordering more ships and containers, but addressing this will take several years. Most of the COVID-19 import disruptions have been eased so many firms are returning to their normal methods of operation. When it came to the issues of public health, there has been a push for major policy reform. The pandemic demonstrated how important federal leadership is to the healthcare system. These reforms include securing the financial arrangements of health professionals to provide all necessary care to groups of patients. This means they are providing payment assistance and arrangements to allow healthcare to be more accessible. Another push is for the under-supported service markets to be improved in the future.

This issue with mental health as a result of Covid-19 is a lingering effect and will not immediately disappear. The plan to address mental health needs is to increase the number of psychiatrists and mental health professionals. Virtual care for underserved communities has been a successful way to meet needs in the short term. The most important improvement for healthcare professionals is to find ways to address burnout and increase flexibility. Having healthy workers is crucial for enhancing patient care and being ready for the next pandemic.

References - Chapter 5

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Afterword

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First and foremost, we, the students enrolled in CHEM 103, Spring ‘23, would like to thank Dr. Amy Shachter, Santa Clara University, for allowing us this opportunity to apply our knowledge and understanding of Chemical knowledge previously learned into a book such as this.

For all 11 of us to complete writing this book in 10 weeks while taking other classes simultaneously was no easy feat. Sitting down and making the time to meet outside of class proved to be rather difficult, so coordinating each of the chapters was quite the challenge. But alas, we hope our hard work paid off and we hope you enjoyed reading this.

Lastly, congratulations to all the seniors graduating this quarter! We wish you all the best for your future endeavors.

Abbreviations and Terminology

- Greenhouse gas
    - A gas that absorbs and emits thermal infrared radiation, resulting in heat being trapped in Earth's atmosphere.
- AQI (Air Quality Index)
    - Scale ranging from 0-500 that is used as a measure for air quality. Lower values indicate better air quality. Each air pollutant has its own AQI sub-index value, which are averaged together for an overall AQI.
- Particulate matter (PM)
    - $PM_{2.5}$ and PM_{10} represent particulate matter 2.5 and 10 micrometers or less in diameter, respectively.
- Carbon dioxide equivalent (CO_2eq)
    - A standard unit for measuring carbon footprints.
- Watt-hour
    - A measurement of energy that represents how many watts (a unit of power) is consumed in one hour.
- PPE
    - Personal Protective Equipment
- Biohazardous materials
    - Waste that is contaminated with things like blood, body fluid, infectious agents, etc. that can pose a threat to human health or the environment.
- Biochemical / physicochemical processes
    - The physical and chemical processes that occur outside and/or inside a cell in order to maintain the balance of homeostasis.
- Biodegradable
    - When something is biodegradable it can be broken down by bacteria or other living organisms.
- Ozone
    - Three oxygen atoms bonded together and found in the stratosphere that protect life on earth from the sun's UV radiation. However, ozone at lower levels of the atmosphere can produce toxic compounds.
- Oxidative stress
    - An imbalance in the body where there are too many unstable molecules (specifically reactive oxygen) and the inability to detoxify/get rid of the unstable molecules.
- Polymer

    - A material consisting of several repeating subunits of large molecules (macromolecules) which can be found naturally or produced synthetically.
- Leachate
    - Can be defined as the water that percolates through the buried waste in the landfill obtaining the chemicals from the waste and leaches or draws out into the soil or into water supplies.
- Autoclave
    - A device that can set up special conditions like extremely high or low temperatures and pressures. It is commonly used with steam under high pressure for sterilization.
- CDC
    - Centers for Disease Control and Prevention, the national public health agency in the United States.
- Carcinogenic
    - Capable of reacting with the body that may cause cancer.
- Mutagenic
    - Capable of causing mutations (changes) to DNA. An example of a mutagen is UV light.
- Teratogenic
    - A substance that is teratogenic is any substance that can cause abnormalities in development of a fetus when the fetus is exposed.
- Genotoxic
    - A substance that is genotoxic can cause damage to someone's DNA through chemical reactions.
- Cytotoxic
    - Refers to something being toxic to cells which can lead to cell death.
- Apolar
    - The absence of polarity. There is no negative or positive end of the molecule.
- Biofilms
    - A layer of microorganisms that have aggregated and are stuck to the outside layer of something.
- Algal blooms
    - When there is a rapid increase/out of control growth in algae in the ocean or freshwater that becomes toxic to other aquatic organisms and even humans.
- Endocytosis
    - A method in which cells take up other substances from the external environment into the cell’s internal environment. This occurs through the

cell surface creating a pocket and internalizing the material by closing off the pocket and creating a “bubble”.

- EPA
  - Environmental Protection Agency
- RCRA
  - Resource Conservation and Recovery Act
- Centrifugation
  - Centrifugation is a mechanical process which involves the use of the centrifugal force to separate particles from a solution according to their size, shape, density, medium viscosity and rotor speed.
- Distillation
  - Distillation, or classical distillation, is the process of separating the components or substances from a liquid mixture by using selective boiling and condensation, usually inside an apparatus known as a still.
- Pyrolysis
  - The pyrolysis process is the thermal decomposition of materials at elevated temperatures, often in an inert atmosphere. Temperature can be understood as thermal vibration. A high temperatures, excessive vibration causes long chain molecules to break into smaller molecules.