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Summer 2023 scientist Nathan Matsumoto studies the allelopathic abilities of California native plants.

Forward

The Headwaters Student Journal showcases the successfully completed research projects from students who participate in the Headwaters Research Experience, a semester-long program where students drive their own research. They ask questions about topics they're interested in, design their experiments, collect and analyze data, and present their findings in presentations and manuscripts.

This issue, we have students from 2022 and 2023 programs who have continued their research efforts after their programs, in order to get robust data and accurately represent their findings. These students all worked hard to see improvement in their scientific research skills, ensure accuracy and reliability in their data, and represent their passions and interests in science.

Many research experience students have aspirations for continued research - whether they're considering a science undergraduate program in college, entering their school science fair, considering careers in the sciences, or continuing to be curious and ask questions. I'm so excited to see how they apply all the skills from the Research Experience in all their future endeavors.

Thank you to our wonderful mentors, who always have insights from their academic and professional careers that help guide these students through complicated datasets, multi-step experimental designs, and complex topics. Mentors are a key piece of the Research Experience, providing individualized support and guidance that students truly value. Students always thank their parents as well for support and guidance through this remote program. From driving to field sites, purchasing equipment, or working through questions, parental support is invaluable to this challenging program!

I am so proud of each student published in this journal. All are incredibly passionate about their research and I cannot wait for what is to come as they become the scientists and problem solvers of the future. Congratulations students! Your hard work shines through these articles.

Courtney Kudera

Data Analyst and Research Experience Program Manager

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STUDENT RESEARCH JOURNAL

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Effects of City Land Use Types on Air Quality in Mountain View, California

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ABSTRACT

All terrestrial organisms use air to breathe, however in the areas that humans live, this air is dirty and sometimes even unhealthy to breathe. Due to how humans use the landscape differently across cities, the air quality may not be the same throughout. Cities would need data to pinpoint zones in cities that need improvement. Therefore, how does air quality differ across different city land use types (City Zoning Codes)? If air quality does differ across city land use types, then parks and recreational areas will have better air quality (in terms of PM2.5 and AQI) than other city land use types (industrial, residential, planned facilities) due to the higher abundance of vegetation and reduced number of cars. As previously stated, I chose to use AQI and PM2.5. AQI (Air Quality Index) to measure non-visible gasses such as CO and SO2, while PM2.5 was used to measure fine air particles such as metals in the air. Data was collected from 8 sites in 4 different zoning codes within Mountain View, California. Results show that PM2.5 and AQI (air quality index) units are significantly lower in parks and recreational areas than other zones . P-values run in the ANOVA test show the relationships between public facilities (public parks) are >0.05 in both PM2.5 and AQI, meaning the data was not by chance. This study suggests that cities could introduce more green areas and public facilities to parts of cities with the worst air quality to improve air quality and reduce air pollution.

INTRODUCTION

Every terrestrial organism on Earth depends on air for survival; therefore, the significance of clean air can mean a great deal to people who are susceptible to poor air quality, as it can be detrimental to even the healthiest humans. The most common ways of measuring air quality are AQI and PM2.5. AQI (Air Quality Index) measures non-visible gasses such as CO and SO2 in the air, while PM2.5 are measures of fine air particles (smaller than 2.5 micrometers) including sulfate, nitrate, ammonium, elemental carbon, and others (1, 2). Despite some individuals being more affected than others, all humans can be negatively affected by poor air quality. The chemicals found in these measurements (e.g., PM2.5 levels above 35 and AQI levels above 100) can increase chances for cardiovascular disease, breast cancer in women, and can cause active children to experience asthma (3). Chemicals found in PM (particulate matter) also cause negative health effects to animals, such as pulmonary and cardiovascular diseases which can lead to premature mortality (Losacco C., 2018). Furthermore, plants are also affected by poor air quality, (4). Negative health impacts including the ones stated previously, show how great of a significance air quality has towards humans and the organisms around us.

Air quality worsens around the world due to an increase of fuel emissions (5), which is evident in our bustling and busy cities. Cities across the world have struggled with poor air quality, which is evident in the more than 6.7 million premature deaths annually caused by respiratory diseases inflicted from air pollution (6). Cities in California for example, have had air related problems for decades (8). Activities such as driving a gas powered car, can cause premature deaths within adults and children, due to the high amount of PM2.5 produced by the burning of diesel and gas fuel (7). In addition, the burning of gas and diesel fuel from the exhaust is the main cause of climate change in the United States (5). This is evident during the Covid-19 lockdown in which the PM2.5 in 10 states decreased by 45.1 units from when it was measured 30 days before the lockdown, likely due to the restriction of using vehicles during lockdown (9). Cities in northern California are leading the movement of clean air with new laws and acts, however many cities such as Los

Angeles aren't making much progress. PM2.5 levels in Los Angeles are 10 units higher than San Francisco, on a daily basis (10). A solution to reduce air pollution are trees. In the United States, trees in urban areas have been shown to reduce 711,000 metric tons of NO2 from the air (11). This amount includes cities across the entirety of the US, including almost 11,000 metric tons from Jacksonville, FL alone. This is around $60.7 million worth of air pollution removed from just one city. (11)

The way people use cities differs between each sector of a town. Therefore, does air quality differ across different city land use types (City Zoning Codes)? If air quality does differ across city land use types, then parks and recreational areas will have better air quality (in terms of PM2.5 and AQI) compared to the downtown and industrial zoning codes due to the higher abundance of trees and the reduction of cars. New research on this under-developed topic will enable a greater understanding on how air quality differs across cities and can help our cities pin-point problem areas, perhaps even cutting down on PM2.5 emissions.

METHODS

I identified 4 different city land use types around Mountain View, California, spanning several city zoning codes, during the summer of 2023. These included public facilities (public parks), precise plans (downtowns), industry, and residential districts (one family housing neighborhoods) (shown in Figure 1). These zones were chosen because I hypothesized that these zones would be the most different from one another. Many of the zones in Mountain View were variants of one another, that may not have had many differences.

Using a Temtop Indoor Air Quality Monitor, I measured the PM2.5 and AQI of the air in 2 different areas of each site within a 6 yard area. I waited for 10 seconds to make sure the monitor was calibrated. Over a 2 week period, I visited each site and took the same measurements 2 times, for a total of 32 replicates.

When deciding where to take the data, the logic changed per zone. In the public facilities, I chose to take measurements in areas not close to the surrounding roads, and close to trees and groves as this would mean a true measurement that wouldn't be changed by outside factors such as car emissions and wind. In residential and industry areas, I decided to take measurements closer to the road, as the buildings within each of the zones were parallel to the street. Furthermore, in precise plan areas, I took measurements closest to the groups of people, as part of my experiment was to see if people's activities affected air quality.

Data analysis was done using ANOVA tests, as this test would be able to be used for more than 3 sites, and would also be able to test the independent and dependent variables in the data. P-value scores lower than 0.05 show that the differences between groups are not by chance and are proven to be significant.

RESULTS

I collected PM2.5 and AQI of various city zones to see if there was a difference in air quality across the city of Mountain View, California. As stated before, PM2.5 measures the particulate matter in surrounding air, while AQI measures the quality of the air, such as how much CO or SO2 is around us (1).

I ran ANOVA tests to see differences in average PM2.5 and AQI units between the zones. Between all the city zones, there were no differences, except for public facilities (parks) which had lower AQI and PM2.5 units compared to other groups. ANOVA tests are used to check differences between the city zoning codes, but specifically, the relationships between the independent and dependent variables in each of the zones. The independent variables for the data collected were PM2.5 and AQI, as they were the variables that changed due to the dependent variable, which was the various City zones . P-values are used to show how likely data differentials are by chance, or due to real results. This means that P-values that are lower than 0.05 are evidence that signifies there is no chance involved, and vice versa for higher P-values. (shown in Table 1 & 2). The P values of the PM2.5 data when comparing public facilities with the other zones was below 0.05, which proves that the differences shown in the figure are not by chance, and therefore, significantly different. This is also true for AQI as the relationships between public facilities and other zones had P-values of <0.01. On the other hand, there were no differences between non-public facility city zones because they have P-values above 0.05.

The data collected (shown in Figures 1A & 1B) concludes that public facilities have significantly lower AQI and PM2.5 when compared to the other city zones. As shown, the mean for PM2.5 in public facilities was around 10 units of particulate matter (PM2.5) lower than the other means. This is also shown in Figure 2B, as the AQI mean is ~50 points lower than the other means. As stated before, the direction of the data was favored towards the public facility, as it is the only one that had a lower mean in both PM2.5 and AQI.

Pair	Mean diff	P-value	Interpretation of P
Precise Plan - Industry	1.46	0.89	Means: **no evidence** that the groups might be different
Public Facility - Industry	-10.4	<0.01	Means: **extremely strong confidence** that the groups are different
R1 Residential - Industry	0.65	0.99	Means: **no evidence** that the groups might be different
Public Facility - Precise Plan	-11.9	<0.01	Means: **extremely strong confidence** that the groups are different
R1 Residential - Precise Plan	-0.813	0.98	Means: **no evidence** that the groups might be different
R1 Residential - Public Facility	11.1	<0.01	Means: **extremely strong confidence** that the groups are different

Table 1: Results of ANOVA test: PM2.5 between different city land use types. Statistical significance between groups is indicated by a p-value < 0.05.

Pair	Mean diff	P-value	Interpretation of P
Precise Plan - Industry	1	1.00	Means: that the groups are **NOT** different
Public Facility - Industry	-37.9	<0.01	Means: **extremely strong confidence** that the groups are different
R1 Residential - Industry	4	0.85	Means: **no evidence** that the groups might be different
Public Facility - Precise Plan	-38.9	<0.01	Means: **extremely strong confidence** that the groups are different
R1 Residential - Precise Plan	3	0.93	Means: **no evidence** that the groups might be different
R1 Residential - Public Facility	41.9	<0.01	Means: **extremely strong confidence** that the groups are different

Table 2: Results of ANOVA test: AQI between different city land use types. Statistical significance between groups is indicated by a p-value < 0.05.

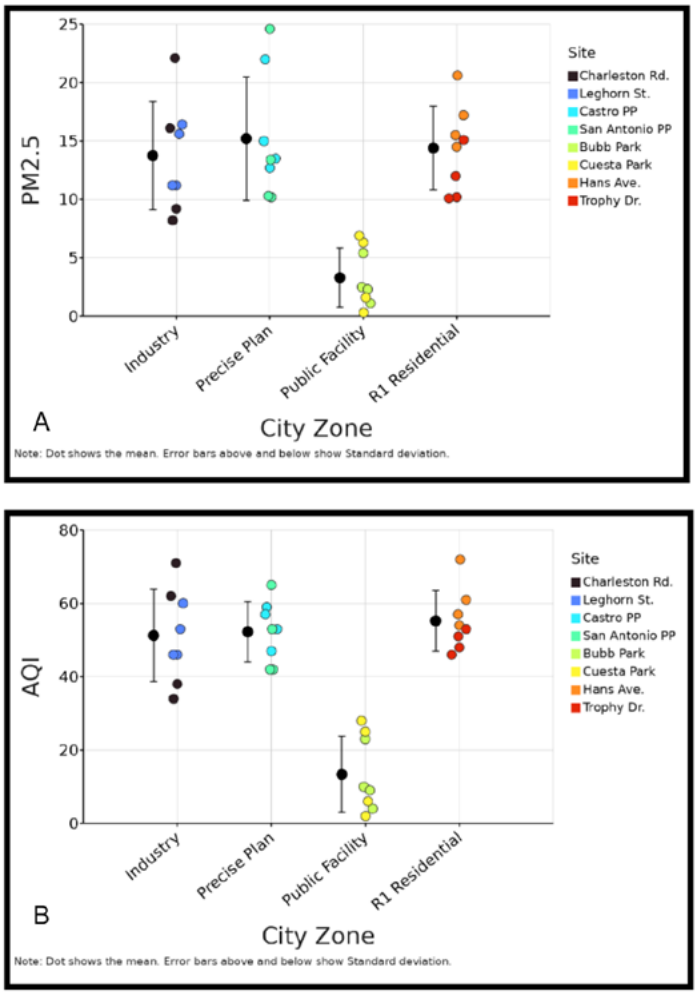

Figure 1A(top) & 1B(bottom): Measurement of air quality across different city land use types in Mountain View, CA depicted as (A) PM2.5 (particle density) and (B) AQI. Sample sizes included 8 sites split between 4 city zones. Public facilities (parks) showed lower AQI and PM2.5 scores compared to other zones (industry, precise plan (downtown areas), and residential)

DISCUSSION

Using a TemTop indoor air quality monitor, I measured air quality measures of PM2.5 and AQI in 4 different city zoning codes to find how air quality differs across a city and to ultimately gain understanding on the role the environment plays on air quality. The result showed a significant difference between the public facilities (parks) and the rest of the zones (residential, industrial, downtown areas).

Though this data does show differences in air quality across an urban environment, it doesn't explain the method of what causes the difference. One reason for this significant difference is that the inclusion of a large amount of trees and the lack of gas-powered cars caused major improvements in the air quality in parks. Trees reduce the wind speed in cities by ~25% and reduce CO2 circulation by ~5% (12). This data could be the reason for the lack of variation in the AQI and PM2.5 units measured in the parks, as wind

carries gas emissions away and towards the monitor. Furthermore, urban trees have been shown to reduce NO2 from the air (11). This could also be the reason for the low AQI and PM2.5 in the parks since there is less NO2 and other chemicals in the air. The results of the data collection have great significance because cities could use this data to improve local air quality. Since parks have lower AQI and PM2.5, this could mean that adding more parks and green spaces to cities could massively improve city air pollution.

Which zoning code needs these green spaces the most, since all of them are so similar? One reason for the similarities could be the lack of differences in the area themselves. While collecting data, I noticed that all of the areas seemed to have the same amount of trees and bushes as one another. Mountain View is littered with trees, and this is the main reason for the similarities between each zone. Parks are different from this because of the lack of cars and the abundance of grass and trees in the area.

Parks do have significantly cleaner air compared to the rest of the city; however, there may have been errors in the data collection that could have swayed the results. First of all, while in the non-public facility zoning codes, measurements had high variation as the units fluctuated between 20 points to >10. To solve this problem, I stood in the same place for around 10 seconds to let the device choose the average per single point of data collected, but this did not always work. This may have been caused by wind carrying car emissions or other particles at some points, while at other, the wind blew the particles away and lowered the score. Additionally, the amount of cars in each area also fluctuated throughout the day, as at some points, cars could be plentiful or streets could be desolate. This fluctuation is illustrated in Figures 2A & 2B, as some scores went way above the mean, while others dropped far below. Last of all, the device used may not have been up to standards compared to high-end equipment, since the price was low and seemed to be made out of cheaper materials. On top of this, the device is supposed to be used for indoor purposes, where the air is much more stable, meaning the device could've had a harder time getting the correct data point.

Though this experiment does yield significant results in terms of how air quality differs across a city, there are more specific areas of research that need to be investigated further. One of these areas is the reasoning behind why parks have so much better air quality. The simple answer is that the trees remove pollution and provide clean air. Different factors like wind and fuel emissions were unable to be unanswered. Another topic of interest to study more are the other city zoning codes that were not included in this study. In this experiment, I chose only 4 out of the 15 different zoning areas in my city. There are still a plethora of other zones left unaccounted. Nonetheless, public facilities' significantly lower AQI and PM2.5; therefore, parks and the abundance of vegetation within them can be used to bring change in our cities and improve local air quality.

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Thank you to my parents, Stuart Tugendreich and Paula Bogard for providing assistance with my transportation needs, as well as funding the research tool used for data collection. I am also grateful for Warren Staver and Bella Kundin for providing me with extremely helpful feedback and editing while writing my manuscript. Lastly, thank you to my peers and teachers, especially Courtney Kudera, at the Headwaters Science Institute Research program for giving feedback during class. Manuscript writing would have been significantly harder without the help of so much support of my classmates and teachers.

REFERENCES

1. W.Gene Tucker, "An overview of PM2.5 sources and control strategies", Fuel Processing Technology, Volumes 65–66, 2000, Pages 379-392, ISSN 0378-3820, https://doi.org/10.1016/S0378-3820(99)00105-8.
2. US EPA. "Particulate Matter (PM) Basics." US EPA, United States Environmental Protection Agency, 2018, www.epa.gov/pm-pollution/particulate-matter-pm-basics.
3. "Air Pollution and Your Health." National Institute of Environmental Health Sciences, www.niehs.nih.gov/health/topics/agents/air-pollution/index.cfm. Accessed 12 July 2023.

4. Winner, William E., and Christopher J. Atkinson. "Absorption of Air Pollution by Plants, and Consequences for Growth." Trends in Ecology & Evolution, vol. 1, no. 1, July 1986, pp. 15–18, https://doi.org/10.1016/0169-5347(86)90061-3
5. "Carbon Pollution from Transportation." EPA, www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation Accessed 12 July 2023.
6. World Health Organization. "Ambient (Outdoor) Air Quality and Health." Who.int, World Health Organization: WHO, 19 Dec. 2022, www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.
7. "Sources of Greenhouse Gas Emissions." United States Environmental Protection Agency, 5 Aug. 2022, www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
8. Lipsitt J, Chan-Golston AM, Liu J, Su J, Zhu Y, Jerrett M. "Spatial analysis of COVID-19 and traffic-related air pollution in Los Angeles". Environ Int. 2021 Aug;153:106531. https://doi.org/10.1016/j.envint.2021.106531
9. Max G. Adam, Phuong T.M. Tran, Rajasekhar Balasubramanian, "Air quality changes in cities during the COVID-19 lockdown: A critical review", Atmospheric Research, Volume 264, 2021, https://doi.org/10.1016/j.atmosres.2021.105823.
10. Numbeo, "Pollution Comparison Between San Francisco and Los Angeles" Numbeo, June 30th, 2023 https://www.numbeo.com/pollution/compare_cities.

Correlation Between Asthmatic Related Illnesses and Emergency Room Check-Ins

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ABSTRACT

The scientific question that I wished to answer at the start of this research experience was the following: How do varying levels of air quality affect the well-being of asthmatic individuals? At the time, my hypothesis was that if air quality declined, the well-being of asthmatic individuals would decline accordingly. This hypothesis was proven correct after thorough data collection. The data sets that I collected were provided through the California Department of Public Health. The reason for using this specific state was due to the fact that California, barring 3 counties, had valid data sets for all 365 days of the year for 55 counties. In addition, the State of California as a whole had also been facing poorer levels of air quality due to widespread wildfires, as experienced throughout the state. I was able to find the number of days in which asthmatic individuals had checked into the emergency room and assumed that about 60% of these check-ins would be poor air quality-related (4)(5). After further research, I could find the number of days that were classified as "Days Unhealthy for Sensitive Groups", and below. This amount was used in correlation with emergency room check-ins to calculate an amount that could signify the number of days in which asthmatics would have checked into the emergency room for poor air-quality-related illnesses. I was able to conclude that poor air quality resulted in several flare-ups for asthmatic individuals residing within 55 of the 58 counties in the State of California; however, there was little to no correlation between poor air quality and emergency room visits related to asthmatic issues.

INTRODUCTION

Throughout the year 2017, the State of California experienced a record-setting number of wildfires spread across the state, resulting in numerous property damages and fatal and non-fatal injuries to innocent citizens. Especially impacted individuals were those who had asthma (2). As defined by the Mayo Clinic, asthma is a condition in which your airways narrow and swell and may produce extra mucus. Asthma can result in several different respiratory issues, the most common being coughing, wheezing, and loss of breath. For some people, asthma is a minor nuisance. For others, it can be a major problem that interferes with daily activities and may lead to a life-threatening asthma attack (1). The wildfires that erupted through the majority of northern California created mass toxic smoke, and this smoke contained several chemicals, including but not limited to carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) (2)(7). All of the listed toxins and the mass exposure of these chemicals into the air, resulted in air quality, on several days of the year, to decline. Air quality can be measured through a scale known as the Air Quality Index (AQI). This index classifies the day's air quality as one of the following categories: "Good", "Moderate", "Unhealthy for Sensitive Groups", "Unhealthy", "Very Unhealthy", and "Hazardous" (1). Asthmatic individuals would be classified as a sensitive group when it comes to AQI. These classifications are used by everyday civilians to find the air quality for their specific location as well as by asthmatics so that they can take specific precautions. In this study, I investigated if a relationship existed between air quality-related variables and asthma-related emergency room visits in 2017.

METHODS

In order to find out how many days needed to be considered hazardous to asthmatic individuals, I had to add the days "harmful for sensitive groups" and the categories above, which came to 147 days. This data was found from the State of California's Health Data web page. More detailed reports were available per county.

One variable which was measured was the number of days throughout the year in which there were days categorized as "harmful for sensitive groups" and more severe categories. Another variable collected was the amount of emergency room visits per county. This data had to be correlated with another variable, which was check-ins that were related to an air-quality related illness (respiratory illnesses that were a result of poor air quality or lack thereof). Through data collection from these various county and state websites (3)(4) I found that there were approximately 3175 emergency room visits and estimated that 60% of these visits were results of air quality-related illnesses. Furthermore, due to a lack of data collection for 3 specific counties (Alameda, Butte, and Tehama) and the fact that these counties' data sets had extreme outliers, they were removed from consideration. After collecting valid data points, I entered the respective data sets into a spreadsheet, and I was able to formulate a scatter plot to depict the various variables and values by inputting values into a Google Sheets spreadsheet, and inserting the respective graphs. After inserting the respective data into the sheet, It displayed the specific points along the graph, and I could insert a line of best fit. After creating this scatter plot through Google Sheets, I had to insert the respective charts into my manuscript document. Furthermore, I added analyses that explored the correlation between the data sets for both charts respectively, to describe what each depicts. Using the R2 feature within Google Sheets, I attempted to find any correlation between the specific data points depicted.

RESULTS

During my study, in order to find the number of days in which asthmatic individuals would have been affected by the air quality, I had to add the totals for the "Unhealthy for Sensitive Groups", "Unhealthy", "Very Unhealthy", and "Hazardous classifications of the Air Quality Index (AQI), I which are classifications considered harmful to asthmatics. After finding the total number of days (147), I then had to calculate the number of emergency room check-ins for asthma-related illnesses. I hypothesized that, considering wildfires took place during the majority of 2017, 60% of all asthma-related emergency room check-ins would be in some way related to the air quality, or lack thereof. The initial number amounted to approximately 3,175 visits. I, however, found that there was little to no correlation between the two data sets due to the R^2 value being 0.001, which translates to a correlation of 0.1%. When days of higher sensitivity for asthmatic individuals occurred, the datasets I acquired from various sources indicated that there were no major differences regarding ER check-ins on normal days versus these days of higher sensitivity.

The correlation between ER visits and asthmatic-sensitive days are graphed in Figure 1. The wide array of scatter plots on the chart further supports this idea. The independent variable within this data set is considered the number of asthmatic-sensitive days, and the dependent variable is the number of ER visits. After producing the R2 value found from these two variables, I found that it resulted in a value of 0.001, which equates to 0.1%, indicating little to no correlation. These results were a vital part of the results of my study, considering that the correlation between ER visits and asthmatic-sensitive days essentially served as one of the answers to my hypothesis.

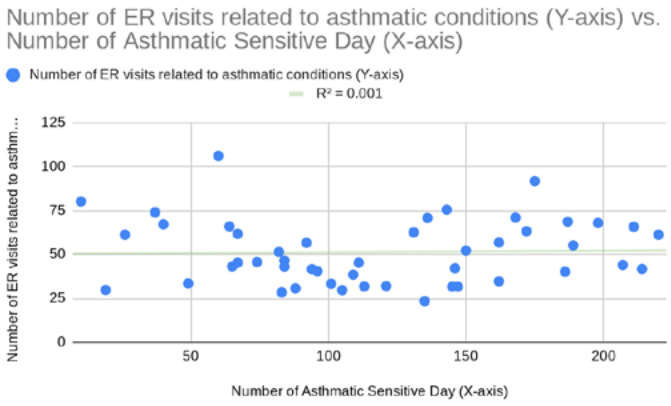

Figure 1: Number of ER visits related to asthmatic conditions vs. Number of Asthmatic Sensitive Day - Correlational Test. The R^2 value found was equal to 0.001 indicating little to no correlation.

Correlation between both values are graphed in Figure 2. For this data set, the numerical values for the independent variable (median AQI) indicate the AQI values at the midpoint of the total data collected, and the dependent variable is the number of visits. The trendline depicts the calculation of R2 as equal to zero, therefore indicating no correlation between the dependent and independent variables. The results of this figure were an important part of my study because the correlation I found between the two variables would show whether there was a correlation between the Median Air Quality Index on specific days, and the emergency room check-ins on those same days which served as a baseline to whether or not my hypothesis was accurate.

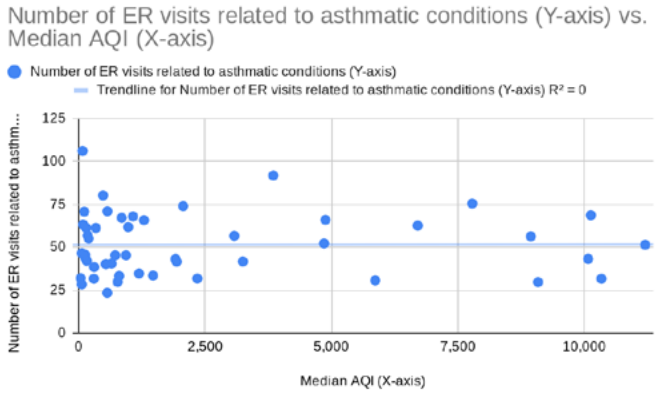

Figure 2: Number of ER visits related to asthmatic conditions vs. Median AQI - Correlational Test. The R^2 value was found to be equal to 0, therefore indicating no correlation between the variables.

DISCUSSION

In order to add context for the study, and gain a better understanding of the baseline for ER visits which related to poor AQI induced illnesses, I calculated the average amount of emergency room visits due to poor air quality-related illnesses. After finding multiple data sets from various different resources I was able to conclude that around 22 emergency room check-ins per day for asthmatics were due to poor air quality-related illnesses (6).The process of arriving at this number includes dividing the number of total ER visits per year that were a result of air-quality related illnesses by the number of days in the year total. I, unfortunately, proved my initial hypothesis as incorrect. Some variables that possibly skewed some of the data sets would have been the number of days on which wildfires took place, the severity of wildfire smoke, the widespread amount of smoke emitted into the environment, and the amount of asthmatic exposure to air. If I could do this experiment again, I would attempt to narrow down the filters of age groups, and potentially the area as well. It would be interesting to see how different age groups reacted differently to asthma. I was able to compare the number of asthmatic sensitive days (calculated with AQI data sets from various counties across the State of California) and median AQI along with the total ER visits for asthmatic-related illnesses. This comparison would show that emergency room visits during this specific time period were related to the poor air quality within the respective areas. A limitation I encountered regarding data collection was the lack of consistent and accurate reporting from all 55 counties. I was unable to collect data from every county in the State of California.

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REFERENCES

1. AirNow.gov. "System Alerts." *AirNow*. gov, 2020, https://www.airnow. gov/?city=Pittsburgh&state=PA&country=USA.
2. Cleland, Stephanie E, et al. "Estimating the Acute Health Impacts of Fire-Originated Pm2.5 Exposure during the 2017 California Wildfires: Sensitivity to Choices of Inputs." *GeoHealth*, 1 July 2021, www. ncbi.nlm.nih.gov/pmc/articles/PMC8247531/.
3. State of California "Asthma Emergency Department Visit Rates." *HealthData.gov, State of California*, 23 Apr. 2022, https://healthdata.gov/State/Asthma-Emergency-Department-Visit-Rates/qhhd-7kyg.
4. State of California. "Asthma Deaths by County" *HealthData.gov, State of California*, 23 Apr. 2022, https://healthdata.gov/State/Asthma-Emergency-Department-Visit-Rates/qhhd-7kyg.
5. CalEnviroScreen, CalEnviroScreen. "Asthma." *Oehha.ca.gov,* 2015, https://oehha.ca.gov/ calenviroscreen/indicator/asthma.
6. Mayo Clinic "Asthma Symptoms & causes" *Mayo Clinic*, https://www.mayoclinic.org/diseases-conditions/asthma/symptoms-causes/syc-20369653
7. American Lung Association "Air Quality Index" *Lung.org*, 11 Sep. 2020, https://www.lung.org/ clean-air/outdoors/air-quality-index
8. Clegern, David. "2020 Saw Steepest Drop in Carbon Pollution Due to the Pandemic | California Air Resources Board." *Homepage | California Air Resources Board*, https://ww2.arb.ca.gov/ news/2020-saw-steepest-drop-carbon-pollution-due-pandemic

Lithium Cobalt Oxide vs Lithium Phosphate Iron Batteries: Which One Is Better for the Environment?

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ABSTRACT

Electric cars are growing in popularity, and these cars use lithium-ion batteries for power. Due to concerns over the impact of the manufacturing of the batteries, an analysis was performed, looking at the environmental impact of lithium cobalt oxide (LCO) and lithium iron phosphate (LFP) batteries in three categories: water use, energy use, and CO2 gas emissions. The impact was compared with the lifetime energy output of the battery to see which type of battery had the least impact per energy output. The environmental impacts were obtained from the Greenhouse gasses, Regulated Emissions, and Energy use in Technologies Model (GREET). This research was not an experiment, but rather an engineering analysis on values to find which battery was better. From this analysis, it was found that LFPs are significantly better than LCOs, being up to 8 times better in certain categories. In all three categories, LFPs had a lower impact to output ratio. This is mainly due to the lack of critical minerals in LFPs, compared to LCOs which contain cobalt. LFPs have been rapidly gaining popularity within electric vehicles.

INTRODUCTION

Electric vehicles (EVs) are rapidly becoming the car of the future. In 2022, more than 10 million cars were sold, and this is expected to reach 14 million in 2023 (1). These cars do not use gasoline, but rather use electricity stored in a battery pack. EVs offer numerous benefits over gasoline powered cars, including no need for a smog check, quick acceleration, and being cheaper to maintain (2). Incentives such as the ones mentioned are some of the reasons these cars are rapidly gaining popularity. These cars also fill a necessity for our environment–they produce no emissions. An average passenger vehicle will produce about 4.6 metric tons of carbon dioxide per year, while electric vehicles will produce zero (3). This is vital because transportation accounted for 37% of global emissions in 2021 (4), which must be curbed in order to prevent global warming.

The main batteries that electric vehicles use are lithium-ion batteries (5). These batteries are made up of electrodes, an anode, cathode, current collectors, and a separator. The electrodes are the positive and negative ends of a cell, which are connected to the current collectors. The current collectors transmit energy between the battery and the device, or in this case, the car. The anode is the negative electrode, while the cathode is the positive electrode. These batteries work by moving lithium ions between the cathode and anode internally. The electrons move in the opposite direction in the external circuit, which provides power. When giving power, lithium ions move from the anode to the cathode, and vice versa when charging (6).

Within lithium ion batteries, there are different types. These different types will be the focus of this research. A common type of lithium-ion batteries are lithium cobalt oxide (LCO). These consist of a lithium cobalt oxide cathode and a graphite anode. It has a high specific energy, but tends to have a low lifespan (7). Currently, these are projected to be the most popular battery type by 2030. Another type of lithium ion batteries are lithium iron phosphate (LFP). These batteries use a lithium iron phosphate cathode, along with a graphite anode. These batteries are very safe, and have a long lifespan, but as a trade-off they have a lower specific energy (7).

The differing materials within these batteries cause them to have unequal environmental impacts. As an example, a tonne of lithium requires 500,000 gallons of water (7). Because electric batteries are supposed to help with the environment, a large concern for the impacts of electric cars is within the batteries, which

produce about 15% to 20% of an EV's lifecycle emissions (8). This brings up the question: which battery will give the best performance per its environmental cost? This research will look at LCOs and LFPs and examine which battery provides the most charge per its environmental impact. It will look at different environmental impacts, these being water usage, energy usage, and CO2 emissions. It will then classify the performance of the battery, and compare.

It is hypothesized that LFP batteries will have the best output for environmental cost. This is because these batteries use iron and phosphate, two common materials, compared to the rarer material of cobalt. Cobalt is rarer so it will most likely be harder to extract.

METHODS

Calculating the ratio of environmental impact to the lifetime energy output of the lithium-ion battery first involved calculating the environmental impact of each battery type. This was done by looking at the amount of impact (ex. CO2 emissions) created from making the cathode for a one kilogram lithium-ion battery. This study first found data on the impact of creating a kilogram of the cathode material from the Greenhouse gasses, Regulated Emissions, and Energy use in Technologies Model (GREET). Then, that value was multiplied by the percent of the battery that is cathode. This gave the proper environmental impact from the cathode of a one kilogram lithium-ion battery. The analysis only looked at the cathode of each battery type, because the other parts of the batteries are made of the same materials, meaning that they would have the same impact on the environment.

This process was done individually with each environmental impact: water usage, energy consumption, and emissions.

To calculate the lifetime energy output of a battery, this study first looked at the energy density of the battery, which was how many watt-hours a kilogram of that type of battery can hold. If a range was given, the average of the two ends was taken. Then, that value was multiplied by the number of charge cycles the battery can perform before needing to be discarded. This gave the total possible lifetime energy output of a one kilogram battery.

From these calculations, the study divided the environmental impact by the lifetime energy output. This gave a number for the environmental impact relative to the lifetime energy output of the battery. Whichever battery has a smaller number is better overall for the environment, factoring in its performance. The overall equation for this is:

$$Environmental\ Impact\left(\frac{units\ will\ vary}{kg\ of\ battery}\right) = impact\left(\frac{units\ will\ vary}{kg\ of\ cathode\ material}\right) \times \frac{kg\ of\ cathode\ material}{kg\ of\ battery}$$

(equation 1): Calculating the environmental impact of a kilogram of battery. Possible units for "units will vary:" mL, g, kJ

$$Lifetime\ Output\left(\frac{kWh}{kg\ of\ battery}\right) = specific\ energy\left(\frac{kWh}{kg\ of\ battery}\right) \times charge\ cycles$$

(equation 2): Calculating the lifetime output. Charge cycles are unitless.

$$Environmental\ Impact\ Ratio = \frac{Environmental\ Impact\ (varied\ units)}{Lifetime\ output\ (kWh)}$$

(equation 3): Calculating final unit of environmental impact ratio.

RESULTS

Electric vehicles (EVs) are rapidly becoming the car of the future. In 2022, mThe analysis was made to figure out which battery would be the best for the environment long term, factoring in its performance. It was done due to the increasing prevalence of electric cars and the need to curb climate change. This was done by finding the environmental impact of each type of battery on water, CO2 emissions, and on energy use. To figure out the impact, the analysis used equation 1. Then, this was compared using equation 3 to the lifetime energy output of the battery, which was found through equation 2. This was to see which battery had the least impact to output ratio. First, the raw values used in equations 1 and 2 were compiled into table 1. Then, the results from those equations were put into table 2. These results were then used to calculate the environmental impact ratio, which was done with equation 3.

Overall, LFP batteries were clearly better for the environment. As seen in table 1, LFPs produced less environmental impact in each category, and had a larger lifetime output. This led to LFPs being 8 times better than LCOs in terms of water usage, 5 times better in terms of CO2 emissions, and finally LFPs being about 5.5 times better in terms of energy usage.

For one KG of:	LCO	LFP
Percent of battery that is cathode (12)	**35%**	**35%**
Raw water usage (9)	**185,600** mL/kg of cathode	**4,2058.5413** mL/kg of cathode
Raw CO_2 emissions (9)	**22,763,600** mg/kg of cathode	**8,816,100** mg/kg of cathode
Energy use (9)	**358** MJ/kg of cathode	**124.979** MJ/kg of cathode
Specific energy (10)	**175** Wh/kg of battery	**125** Wh/kg of battery
Charge cycles (11)	**750**	**2000**

Table 1: Used in equations 1 and 2. Raw values taken from GREET model and sources 10, 11, 12.

	LCO	LFP
Water usage	**64,960** mL/kg of battery	**14,720.49** mL/kg of battery
CO_2 emissions	**7,967.26** g/kg of battery	**3,085.64** g/kg of battery
Energy use	**125,300** kJ/kg of battery	**43,742.65 kJ**/kg of battery
Lifetime output	**131.25** kWh/kg of battery	**250 k**Wh/kg of battery

Table 2: Results from using equations 1 and 2. Values in table used in equation 3. Equation 1 used for calculating water usage, CO2 emissions, and energy use. Equation 2 used for calculating lifetime output.

	LCO	LFP
Ratio for water usage:	**490** mL/kWh	**60** mL/kWh
Ratio for CO_2 emissions:	**60.7** g/kWh	**12.34** g/kWh
Ratio for energy use:	**954.67** kJ/kWh	**174.97** kJ/kWh

Table 3: Final calculations of environmental impact ratio using equation 3.

DISCUSSION

LFP batteries are clearly better for the environment, being up to 8 times better than LCOs, according to this analysis. They were better in all three categories examined, these being CO2 emissions, energy use, and water use. These results are mainly due to how LFPs do not contain cobalt, which is considered a critical material for energy. Meanwhile, the materials for an LFP (excluding lithium) cathode are not considered a critical material for energy (15). The materials in an LFP battery are much more common and easier to find.

There could be some sources of error in the final numbers. For example, when calculating the lifetime output of each battery, it was assumed that these batteries would have a 100% capacity throughout all its cycles. It is known that lithium-ion batteries

consistently lose charge capacity over time (13). This could have skewed the final ratios to seem lower than reality.

Another possible error could be in the calculation of the environmental impact of a kilogram of the battery. Due to only examining the impact of the cathode; this analysis disregarded the other parts of the battery. Differences exist between types of lithium ion batteries in the cathode material, meaning that the relative difference between the final numbers of this analysis are still accurate (14).

From these analyses, it is clear LFPs should be preferred over LCOs. Thankfully, electric battery companies have started to notice this. LFPs have reached their highest market share in the past decade, at about 30%. They are the second most popular battery, and are only below lithium nickel manganese cobalt oxide batteries, which have a share of 60%. Car brands such as Tesla have been using more LFP batteries, going from 20% of use in 2021 to 30% in 2022 (15).

A potential change to this study is examining the whole battery, not only the cathode. This would allow for precise numbers, which could be used in determining . Additionally, while these numbers definitively show that LFPs are better than LCOs, follow-up studies are necessary to examine whether LFPs are the best type of battery for cars across the board. There are many different types of batteries, and it is important to compare all the battery types.

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REFERENCES

1. Global EV Outlook 2023 Catching up with Climate Ambitions. iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf.
2. California Air Resources Board. "Battery-Electric Cars | DriveClean." Ca.gov, 2021, driveclean.ca.gov/battery-electric. Accessed 5 July 2023.
3. EPA. "Tailpipe Greenhouse Gas Emissions from a Typical Passenger Vehicle | US EPA." US EPA, 30 May 2023, www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle#tailpipe-emissions. Accessed 5 July 2023.
4. Transport – Topics - IEA. "Transport – Topics - IEA." IEA, 2021, www.iea.org/topics/transport. Accessed 5 July 2023.
5. "Alternative Fuels Data Center: Batteries for Electric Vehicles." Energy.gov, 2020, afdc.energy.gov/vehicles/electric_batteries.html. Accessed 17 July 2023.
6. "What Are Lithium-Ion Batteries? | UL Research Institutes." Ul.org, 2022, ul.org/research/electrochemical-safety/getting-started-electrochemical-safety/what-are-lithium-ion. Accessed 5 July 2023.
7. Battery University. "Battery University." Battery University, 19 Sept. 2010, batteryuniversity.com/article/bu-205-types-of-lithium-ion. Accessed 5 July 2023.
8. Bieker, Georg. A GLOBAL COMPARISON of the LIFE-CYCLE GREENHOUSE GAS EMISSIONS of COMBUSTION ENGINE and ELECTRIC PASSENGER CARS. 2021, theicct.org/wp-content/uploads/2021/07/Global-Vehicle-LCA-White-Paper-A4-revised-v2.pdf.
9. Wang, Michael, Elgowainy, Amgad, Lu, Zifeng, Baek, Kwang H., Bafana, Adarsh, Benavides, Pahola T., Burnham, Andrew, Cai, Hao, Cappello, Vincenzo, Chen, Peter, Gan, Yu, Gracida-Alvarez, Ulises R., Hawkins, Troy R., Iyer, Rakesh K., Kelly, Jarod C., Kim, Taemin, Kumar, Shishir, Kwon, Hoyoung, Lee, Kyuha, Lee, Uisung, Liu, Xinyu, Masum, Farhad, Ng, Clarence, Ou, Longwen, Reddi, Krishna, Siddique, Nazib, Sun, Pingping, Vyawahare, Pradeep, Xu, Hui, and Zaimes, George. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 .Net). Computer Software. USDOE Office of Energy Efficiency and Renewable Energy (EERE). 10 Oct. 2022. Web. doi:10.11578/GREET-Net-2022/dc.20220908.2.

10. Cloud, Maria. "What Is the Energy Density of a Lithium-Ion Battery?" Fluxpower.com, 2020, www.fluxpower.com/blog/what-is-the-energy-density-of-a-lithium-ion-battery. Accessed 23 July 2023.
11. "Lithium-Ion Batteries Overview." Capacitorsite.com, 2023, www.capacitorsite.com/lithium.html. Accessed 23 July 2023.
12. Jacoby, Mitch. "It's Time to Recycle Lithium-Ion Batteries." Chemical & Engineering News, American Chemical Society, 2019, cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28. Accessed 23 July 2023.
13. Tektronix. Lithium-Ion Battery Maintenance. www.newark.com/pdfs/techarticles/tektronix/LIBMG.pdf. Accessed 24 July 2023.
14. Berthold, Emma. "Lithium-Ion Batteries." Australian Academy of Science, Nova, 15 Mar. 2016, www.science.org.au/curious/technology-future/lithium-ion-batteries. Accessed 24 July 2023.
15. Energy.gov. "What Are Critical Materials and Critical Minerals?" Energy.gov, 2020, www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals. Accessed 24 July 2023.
16. IEA. "Trends in Batteries – Global EV Outlook 2023 – Analysis - IEA." Global EV Outlook 2023, 2023, www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries. Accessed 24 July 2023.
17. Amit Katwala. "The Spiralling Environmental Cost of Our Lithium Battery Addiction." WIRED UK, WIRED UK, 5 Aug. 2018, www.wired.co.uk/article/lithium-batteries-environment-impact. Accessed 24 July 2023.

Cole Greene , Summer 2023 student, collects water samples.