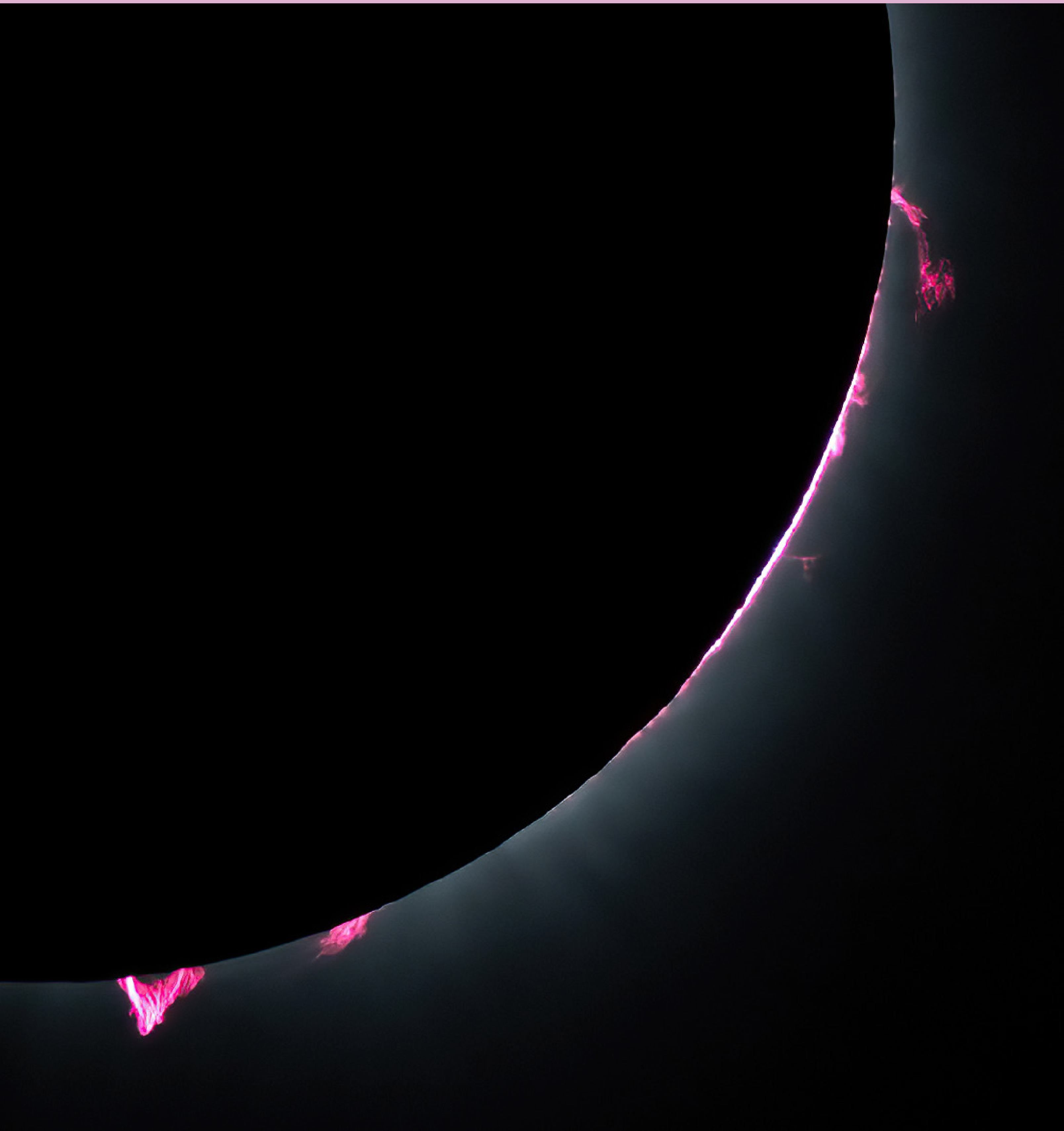
THE TOWER

Undergraduate Research Journal at Georgia Institute of Technology

SPRING '24



THE TOWER

Letter from the Editors

Dear Reader,

Thank you for picking up the Spring 2024 Issue of *The Tower*, Georgia Tech's undergraduate research journal. The journal has had a tumultuous history since first being published in 2008. However, thanks to the amazing community of staff and faculty at Tech dedicated to exposing undergrads to research – even a global pandemic could not halt our publication for long.

Within our first issue with new research in nearly four years, you will find a diverse array of work spanning various disciplines. From groundbreaking scientific discoveries to insightful analyses of societal issues, *The Tower* stands as a testament to the depth and breadth of undergraduate research conducted by Georgia Tech undergraduate students.

As the editors of this publication and fellow undergraduate researchers, we are continually inspired by the creativity and ingenuity displayed by our contributors. We would like to extend our thanks to the authors for entrusting us with their work, as well as our amazing staff for their invaluable contributions in ensuring the quality and rigor of the research presented herein. Their dedication and expertise were instrumental in restarting our journal and upholding its academic integrity.

To our readers: we encourage you to immerse yourself in the thought-provoking articles contained within these pages. Whether you are a fellow researcher, an educator, or simply someone with a keen interest in learning, we are certain that you will find inspiration and insight within these pages.

We would also like to express our appreciation to the faculty advisors, administrative staff, and supporters who have played a vital role in making this publication possible. Namely Dr. Laura Williams, Director of Undergraduate Research, and Mac Pitts, Director for Student Media, who have been instrumental in supporting us support the next generation of scholars and innovators.

Thank you for joining us at *The Tower* on this journey of exploration and discovery.

Regards,
Alexander Dubé & Anush Singhal
Editors-in-Chief of *The Tower*
2023-24

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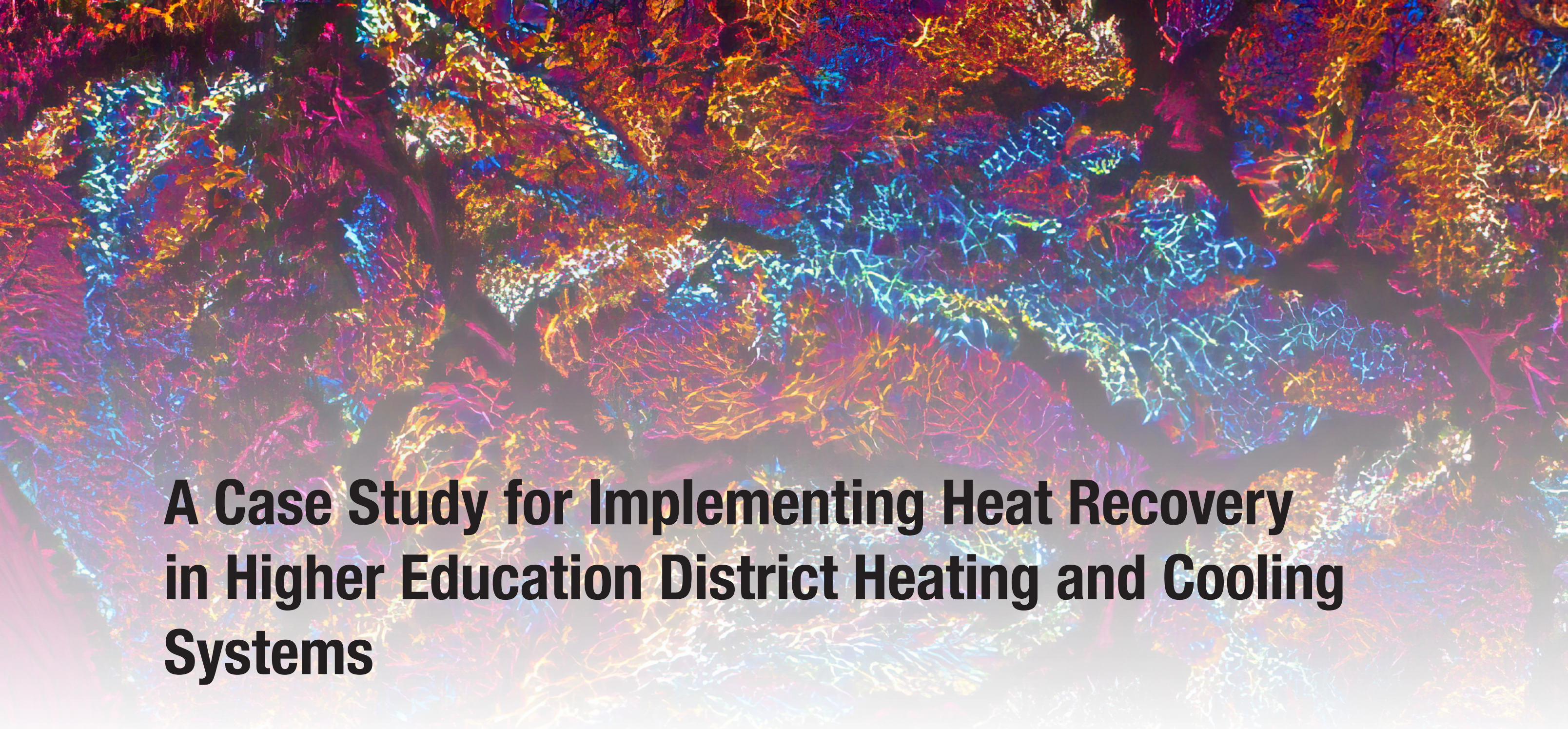

A Case Study for Implementing Heat Recovery in Higher Education District Heating and Cooling Systems

John Schmidt[1], Rohan Datta[2], Victory Ekpekurede[3], Jason Juang[4]

ElectrifyGT is a sustainability consulting student organization focused on helping Georgia Tech economically reach their sustainability goals. We believe that electrification is the fastest, most effective means for reducing campus greenhouse gas emissions, and the cost savings and public health benefits associated with electrification make this issue critical to long- and short-term campus planning at Georgia Tech. We work by engaging key stakeholders and providing research and resources to aid in a responsible transition.

Acknowledgements

We are incredibly thankful to Georgia Tech Infrastructure & Sustainability for supporting this research with their data. We would like to acknowledge the Carbon Reduction Challenge for inspiring our team to provide the initial investigation that created the baseline for this report. We thank ElectrifyGT and the members of the Building Efficiency project team for their continued support and membership in creating high quality research for this report.

Abstract

The heating and cooling of buildings, along with other construction-related fossil fuel combustion, accounts for nearly 30% of the United States' carbon emissions. Research institutions like Georgia Tech may report even higher greenhouse gas (GHG) emissions from these activities, attributed to their more energy-intensive buildings. Many campuses use district heating and cooling systems (DHCS) for heating and cooling of their buildings. However, these legacy systems pose safety risks, incur higher maintenance costs, and offer limited flexibility in heat generation. The potential of heat recovery–integrated with hot water distribution infrastructure–to address these challenges remains underexplored in university settings. This study explores a scenario in which waste heat from the cooling process is repurposed using heat recovery chillers at Georgia Tech's Holland Plant, part of its DHCS. This approach could lead to annual utility savings of $2.5 million and a reduction in carbon emissions by 15,000 metric tons.

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Introduction

Climate change poses a significant threat to both planetary health and humanity's well-being. Models published by the Intergovernmental Panel on Climate Change (IPCC) suggest that it is possible to limit earth's warming to within 1.5 °C and avoid the most pressing effects of climate change, but current policies and practices put the world on track for a devastating 3.2 °C of warming. Preventing this requires sweeping action since current fossil fuel infrastructure already exceeds the carbon budget of the 1.5 °C pathway if allowed to burn until end of life (IPCC, 2023). On the other hand, renewable electricity generation exceeded that of nuclear and coal in 2022 (EIA, 2023) and, if available, is often the cheapest form of energy (La Camera, 2022). To capitalize on these rapid developments, fossil fuel infrastructure must be converted to support viable electric alternatives where possible in a point-source replacement strategy known as electrification.

The Georgia Institute of Technology (Georgia Tech) experiences year-round simultaneous demand for heating and cooling (Figure 1), which presents a unique opportunity to use waste heat produced in the process of cooling water to provide on-campus heating, a strategy referred to as heat recovery. Here, we present a feasibility analysis for one scenario of point-source electrification in Georgia Tech's district heating and cooling system (DHCS) housed at the Holland Plant. Specifically, we explore how heat recovery chillers and a low-grade hot water distribution system (HWDS) would allow the system to capture the waste heat currently released through plant's cooling tower.

We illustrate how the implementation of heat recovery on campus would shift a substantial portion of the heating load away from natural gas, significantly decreasing Georgia Tech's Scope 1 carbon emissions–direct GHG emissions from an organization–and yield notable financial savings. Additionally, electrification offers co-benefits on campus such as improved air quality, enhanced campus infrastructure, energy flexibility for installation of new renewable low-grade heat sources, and a leadership role in sustainability among higher education institutions.

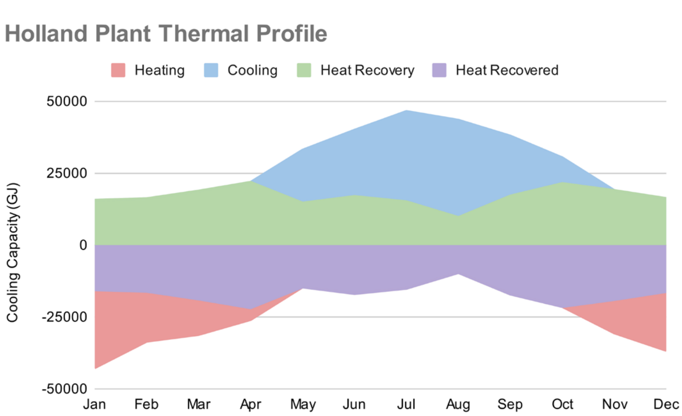

Figure 1. Thermal profile of Georgia Tech's Holland Plant heating (red) and cooling (blue) loads (GT I&S), the potential area for Heat Recovery (green), and the area for Recovered Heat (purple)

Methods

To simplify the analysis, this study is centered solely on the evaluation of Georgia Tech's Holland Plant, one of the plants in the broader district heating and cooling network. We first calculate and present annual costs and emissions from the status quo usage of natural gas (NG) boilers, electric chillers, and water in the cooling tower. We then present a scenario in which heat-recovery chillers, which capture and utilize the waste heat generated from the process of chilling water, are implemented to replace heat generated from natural gas in the overall heating load. Both scenarios leverage actual usage and cost data provided by Georgia Tech's Infrastructure and Sustainability office, averaged over a 5-year period from June 2017 to May 2022.

It is important to note for both the cost-analysis calculation and the overall study that low grade heat recovery as proposed in this study is not favorable for steam generation. The current Georgia Tech system, which relies heavily on steam, would need to be converted to a HWDS. This conversion can be costly: most of the associated upfront costs and obstacles to implementation come from this one issue.

We now share our calculations of potential savings. Due to the detailed data available, calculating potential savings required devising simple equations for NG (eq. 1) and Electrode Boiler (eq. 2) energy usage in a heat recovery scenario, NG makeup of output steam energy (eq. 3), and NG boiler efficiency (eq. 4).

$$NG_{HR} = \frac{(S - C_E * HR) * M_{NG}}{G_{EF}} \tag{1}$$

$$EB_{HR} = \frac{(S - C_E * HR) * (1 - M_{NG})}{E_{EF}} \tag{2}$$

$$M_{NG} = \frac{G_E}{G_E + E_E} \tag{3}$$

$$G_{EF} = \frac{S - (E_E * E_{EF})}{G_E} \tag{4}$$

Values NG_{HR} and EB_{HR} represent energy outputs required from the NG and electrode boilers, respectively. M_{NG} represents the proportion of the steam energy coming from NG boilers. G_{EF} is the calculated real efficiency of the NG boilers. S, C_E, G_E, and E_E are steam, chiller, NG boiler, and electrode boiler energy, respectively. HR is heat recovery potential. G_{EF} and E_{EF} are NG and electrode boiler efficiencies, respectively. All other inputs were directly provided from Georgia Tech Infrastructure & Sustainability.

We now evaluate the data provided by Georgia Tech. Annual cost and carbon calculations make use of this data by subtracting the excess energy, defined as the amount of heating energy not met by reclaimed heat in eqs. 1 & 2, from the total amount of energy being used to heat water in the status quo scenario. This calculation is key to uncovering the potential energy savings, as only that excess amount should be accounted for in calculating the heat recovery scenario's carbon emissions and cost. The cost savings on an annual basis are then taken into account along with the estimated upfront capital investment required to implement a project to this scale.

To estimate the total investment, we rely on economic parameters pulled from peer-reviewed publications. To estimate the cost of purchasing new equipment for the Holland Plant, we use an equation for the initial cost of purchasing heat pumps (eq. 5)

$$C_{HP} = a * (c^b) * c \tag{5}$$

where a and b are provided economic parameters, and c represents the system's capacity (Abokersh et al., 2020).

The estimated cost of new equipment is added to the total installation cost of converting the existing steam systems to a HWDS and retrofitting buildings to be able to receive and use hot water. We estimate this implementation cost using studies published by Stanford University during and after major upgrades to their energy systems (SESI, 2016). Stanford's campus heating and cooling upgrade involved converting 154 buildings over 3 years, building an entirely new central energy facility, laying new piping for their hot water distribution system (HWDS), and constructing a new small-scale NG plant for remaining heating needs. After finding the average retrofit cost per building and the unit cost of distribution network upgrades, we extrapolate those values to the buildings serviced by the Holland Plant and the approximate area covered by its steam distribution infrastructure.

The conversion from waste heat energy to usable energy is predicated on the heat recovery coefficient HR, a ratio of the amount of heat generated from chilling water to the amount of cooling work done. This coefficient varies depending on equipment used, so this study relies on real usage data from the Stanford model (SESI, 2016).

Results

Our analysis estimates that the Holland plant currently emits an average of 27,454 metric tons of Scope 1 and 2 (indirect GHG emissions associated with the purchase of electricity) CO2 equivalent emissions (mtCO2e) annually, and the direct cost to Georgia Tech associated with purchasing these utilities is $8,812,974 per year on average. In our proposed HR scenario, however, total emissions are estimated to be 12,756 mtCO2e and total utility costs are $6,286,475. This yields potential savings of $2,526,499 and 14,699 mtCO2e each year, a reduction by about 29% in costs and over 50% in carbon. Figure 2 and Figure 3 show breakdowns of the biggest contributors to the annual costs and carbon emissions.

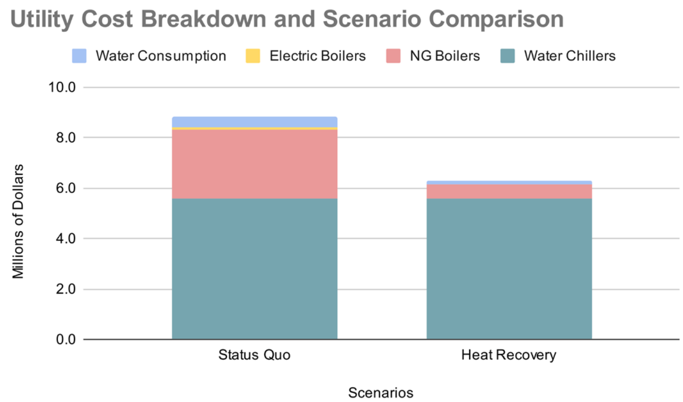

Figure 2. Total annual utility cost breakdown for both current and HR scenarios.

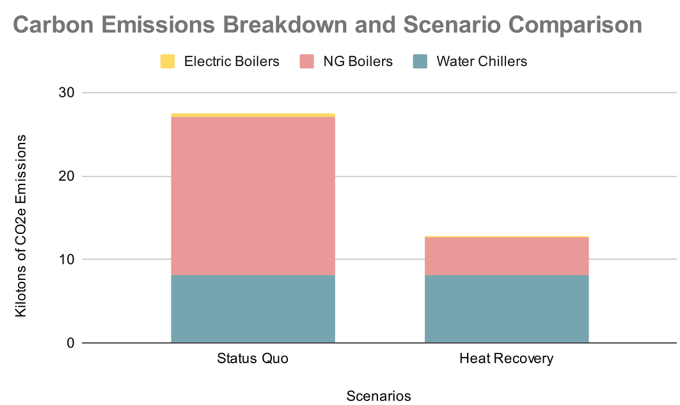

Figure 3. Total annual carbon emission breakdown for both current and HR scenarios.

The final estimated initial cost factoring in Holland Plant conversion, new hot water distribution infrastructure, and building conversions is $13,058,271. We utilize this upfront investment cost in a cost analysis along with an annual maintenance cost and a contingency factor, which yields an upper bound on upfront cost of around $16 million. With annual savings of about $2.5 million, this results in a payback period less than seven years (see Figure 4). The significance of this payback period is amplified when considering that the lifespan of a heat pump is 20-25 years (Self, 2013). Considering the scale of the transformation for Georgia Tech's infrastructure, the speed at which this project could pay itself off is a testament to the potential of heat recovery and electrification in a DHCS.

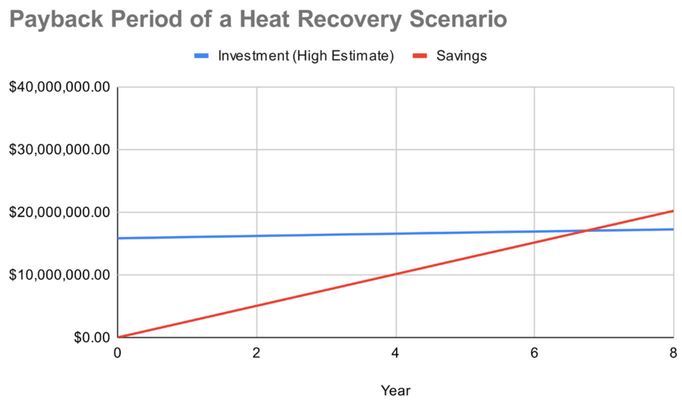

Figure 4. Payback period over 12 months given utility savings and upfront equipment investment in a HR scenario.

Reducing almost 15,000 mtCO2e of carbon emissions from heating and cooling part of campus is certainly impressive, but it can be difficult to conceptualize the magnitude of the savings without benchmarks. To provide more context to these numbers, a typical passenger vehicle in the United States emits about 4.6 mtCO2e per year (EPA, 2023), so our calculated carbon savings are equivalent to eliminating the annual emissions from over 3,000 vehicles. These are already meaningful numbers and are further enhanced by the potential for continued improvements.

Discussion

Along with the carbon and cost savings, updating the Holland Plant with electrified heating and cooling infrastructure has a myriad of co-benefits for Georgia Tech and the campus community. First, the current heating and cooling infrastructure operated by Georgia Tech is the biggest producer of Scope 1 (on-campus) emissions. By minimizing the burning of natural gas on campus, the Institute can eliminate the majority of these emissions and improve the air quality–an especially important health metric for the city–for students, faculty, and staff.

The current fossil-fuel infrastructure is also reaching the end of its functional lifespan; the boilers were installed in 1962, and many of the chillers were replaced in 1998 (with a typical 25-year lifecycle). Thus, we do not attempt to calculate the remaining monetary value of the existing boiler infrastructure to factor into our financial analysis. Further, we expect the long-term costs of operating the Holland plant as it exists today to be much higher than the long-term costs associated with an electrified system because of this dated infrastructure. This assumption is supported by Stanford's estimates, which list their "business as usual" scenario as the one with the lowest upfront cost but highest lifetime costs weighed against all other scenarios (Stanford University Office of Sustainability, 2015).

Finally, the transition to an electrified district heating and cooling system provides the Institute with a large capacity for energy flexibility. The source of electricity for new system can come from on-campus renewables such as rooftop solar or from a grid equipped with a greater renewables percentage. This flexibility will allow for the most cost-effective energy use and reduce the carbon emissions even more than anticipated as the Georgia Power energy grid becomes greener (Center for the New Energy Economy, 2022). Recent publications on 4th and 5th generation DHCS options also provide a vision for what hyper-efficient and sustainable heating and cooling systems will look like moving forward, incorporating more alternative heat generation sources and greener grid energy mixes (Abokersh et al., 2020). Even though Georgia Tech experiences simultaneous heating and cooling year-round, the amount of recovered heat available for use is bound during the winter months since the heat generated by chilling water does not meet the dominant heating load. Additional heat production capacity must then be installed; this could come from carbon-based NG boilers or more nascent technologies such as solar thermal energy or long term thermal energy storage. Building a truly balanced, cost-effective, and carbon neutral district heating and cooling system in the United States should be the focus of additional research moving forward.

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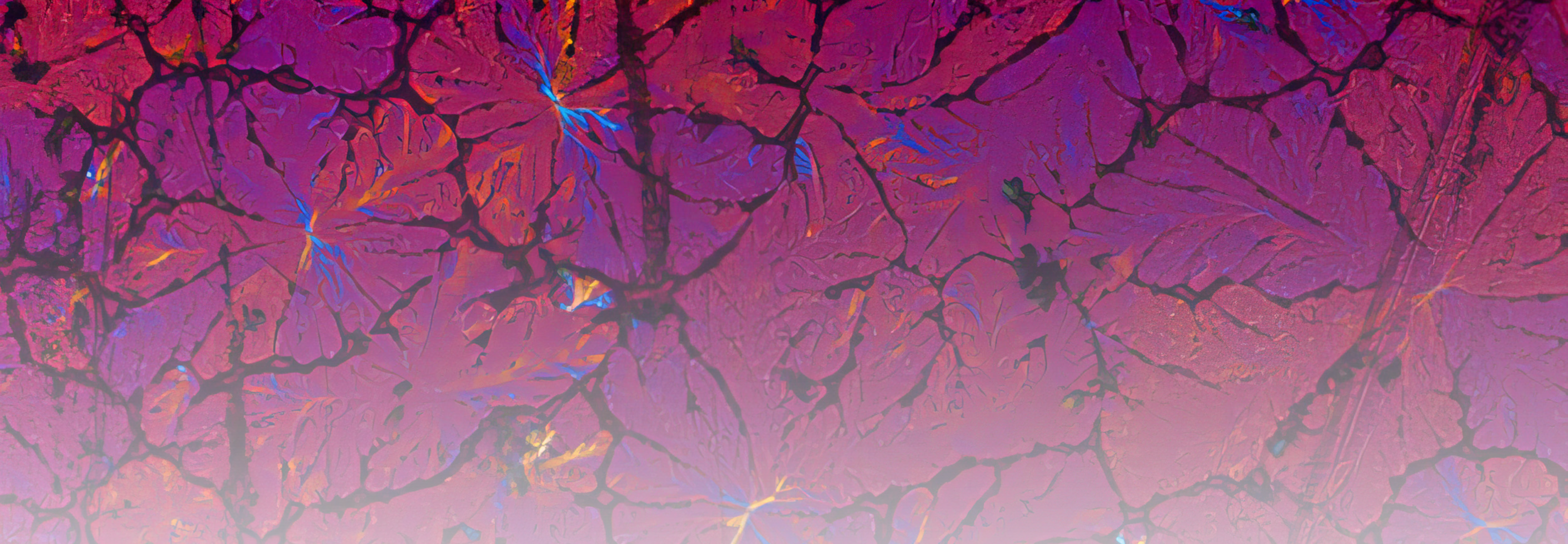

Forever Chemicals, Evolving Laws: Navigating the Current Landscape of PFAS Mitigation

Olivia Quern[1]

Olivia Quern is a third-year undergraduate student at Georgia Tech majoring in International Affairs and French and minoring in Biology. Having grown up in Singapore, Dubai, and Georgia, she developed a deep appreciation for nature, which has grown into a strong passion for environmental protection. Her experiences include working at the French Consulate in Atlanta and the U.S. Department of State's Office of Conservation and Water in Washington D.C. Post-undergrad, she plans to pursue a J.D. with a focus on environmental law, particularly in environmental justice and pollution mitigation. In her free time, she enjoys reading at the park and exploring new cafes with friends.

Abstract

Per- and polyfluoroalkyl substances (PFAS) contamination in tap water presents significant environmental and public health concerns in the United States. PFAS, commonly known as "forever chemicals," have been widely used throughout industries for decades, contributing to their ubiquitous presence. Various levels of governance have proposed or implemented measures aimed at PFAS mitigation, including the establishment of drinking water standards, infrastructure remediation, and environmental responsibility acts focused on pollution cleanup. Additionally, multidistrict litigation, Supreme Court cases, and EU actions have influenced the process of addressing PFAS pollution, prompting important questions about the responsibility for safeguarding natural resources and communities. This paper provides a holistic examination of how PFAS is being addressed by reviewing current PFAS legislation and litigation, discussing the implications of Supreme Court cases on the federal government's scope of environmental protections, and exploring how environmental issues can and have been addressed in the absence of established laws and protections.

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Introduction

The issue of per- and polyfluoroalkyl substance (PFAS) pollution has garnered increasing attention as a recent study sheds light on the extent of chemical contamination in tap water across the United States. In July 2023, the U.S. Geological Survey published its findings encompassing both private and public water supplies, revealing an alarming reality: at least 45% of the nation's tap water is likely contaminated with one or more types of PFAS.[1] These chemicals, notoriously known for their long-lasting presence in the environment, present a multi-faceted issue for water quality, public health, and environmental protection. This disconcerting discovery underscores the pervasiveness and severity of PFAS contamination across the nation.

Background

Per- and polyfluoroalkyl substances are a group of over 12,000 manmade chemicals utilized in various industrial sectors since the 1940s.[2] PFAS' oil and water-repelling properties led to their widespread incorporation in nonstick and stain-resistant products, ranging from firefighting foams and cookware to cosmetic products and fabrics.[3] The same bonds that create PFAS' water and oil-resistant properties are also responsible for their extremely slow degradation and bioaccumulation, earning them their widely recognized nickname: forever chemicals.[4]

The two most common types of forever chemicals are lab-created substances called Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS).[5] These two chemicals are the major per- and polyfluoroalkyl substances currently targeted by government regulations. While PFOA and PFOS chemicals are no longer manufactured in the United States due to their harm, other countries continue to incorporate these types of PFAS in their U.S.-imported products, perpetuating the growing contamination issue in the U.S. [6] Over the past few decades, the impact of PFAS have been increasingly researched as reports of adverse health effects from exposed workers and affected citizens emerge.[7] Drinking contaminated water is the primary means of exposure to PFAS alongside breathing in the chemicals, ingesting contaminated food, and using products made with PFAS. These contamination pathways contribute to a spectrum of problems including high blood pressure, decreased fertility, and numerous cancers.[8] The extensive variants of PFAS cause their harmful properties to manifest differently in people, making it increasingly difficult to understand the extent of the chemicals' direct health effects.[9] In addition to the negative impact on people's health, PFAS have contributed to the degradation of the environment as the chemicals migrate via runoff into waterways and the soil, consequently compounding in produce and animals.[10]

Given our current understanding of PFAS and the uncertainties surrounding their effects, the absence of regulation could result in extensive repercussions for public health and ecosystems. Both federal and state governments are currently making progress on restricting PFAS through various legislative efforts; while proposals for imposing restrictions have been made, the necessity and severity of these laws are a contentious topic. The extent of this issue, permanence of PFAS, and political polarization of environmental efforts only make the task of preventing and mitigating the detrimental effects of these chemicals much harder to navigate, but progress has been made at various levels of governance.

Federal Action

Bipartisan Infrastructure Law (BIL)

Due to the increasing concerns about PFAS' effects, the Biden Administration has been pushing legislation to mitigate these problems. In February of 2023, President Biden pledged $9 billion to tackle PFAS contaminants in drinking water and support disproportionately affected communities under the Bipartisan Infrastructure Law.[11] With these large federal investments, the Bipartisan Infrastructure Law aims to help improve infrastructure to curb water pollution and enhance the feasibility of water quality testing.[12] These provisions to upgrade and modernize water infrastructure hold the potential to ensure communities' access to safe drinking water. Additionally, the research funded under the federal initiative will identify effective PFAS treatment and remediation methods. The White House Office of Science and Technology Policy recently released a report detailing current knowledge of PFAS, safer chemical substitutes, and how the office will collaborate with federal agencies to implement the administration's PFAS reduction goals outlined in the Bipartisan Infrastructure Law.[13] By distributing these resources and knowledge, communities can become informed on PFAS, their prevalence, and steps being taken to combat pollution locally. The combination of increasing education within local communities and collaboration between scientific institutions, government agencies, and industry experts, sets a foundation for greater nationwide cooperation to safeguard public health and the environment against the persistent challenges posed by PFAS.

Justice 40

Through the collective efforts embedded in the Bipartisan Infrastructure Law, it becomes critical to redirect increased attention toward underserved areas where resource accessibility is limited. This is crucial to ensure the comprehensive enforcement of environmental standards across the country. The introduction of the Justice 40 initiative brings light to public and environmental health disparities in the U.S. as well as the importance of racial and socioeconomic intersectionality in environmental justice.[14] This program has pledged to allocate 40 percent of federal investments to disadvantaged communities by implementing affordable and sustainable housing, transportation, energy, and pollution remediation.[15] Within the Justice 40 initiative, the Biden administration has articulated the need to "transform hundreds of Federal programs" including projects within the Department of Agriculture and Energy to remediate widespread and pervasive environmental inequalities.[16] In order for reforms to take place, the White House has outlined various guidelines for federal agencies to follow, many of which are currently being expanded to tackle PFAS pollution.[17] This ambitious initiative requires extensive reforms in the Federal government, which will presumably take years of extensive collaboration, negotiation, and consensus-building among agencies, but if successfully executed, can drastically reduce the environmental disparities found throughout the U.S.

Drinking Water Standards

In accordance with the Biden Administration, the Environmental Protection Agency (EPA) proposed its first drinking water standards for PFAS in March of 2023.[18] This limit on PFAS concentrations encompasses six chemicals, setting individual restrictions of 4 parts per trillion for PFOA and PFOS and a restriction for a mixture of PFAS – PFNA, PFHxS, PFBS, and GenX Chemicals to ensure that the harm of the combination of these chemicals is restrained.[19] This EPA proposal tackles the most prevalent per- and polyfluoroalkyl substances and a mixture to address a substantial portion of PFAS contaminants and minimize the greater effect that a combined mixture of per- and polyfluoroalkyl substances have on human health.[20] The proposal of the rigorous constraint is motivated by the recognized adverse consequences associated with PFAS contamination. This restriction is equivalent to a time frame of just 1 second in 8,000 years.

Following its announcement of the drinking water standard, The EPA added the PFAS proposal to the Federal Register, a government publication used for announcing proposed regulations and soliciting public input. In 2022, the EPA outlined intentions and rationale for the drinking water standard and opened the topic up for public discussion for comments from concerned parties, ranging from scientific experts to citizens.[21] This process, crucial for government transparency, is implemented to disseminate information and contribute to developing scientifically sound regulatory standards aimed at safeguarding public and environmental health from the adverse effects of PFAS contamination. By quantifying a stringent limit, this drinking water standard, if implemented, will set a foundation for future regulations and can encourage other parties to enact policies that follow suit.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and National Oil and Hazardous Substances Pollution Contingency Plan (NCP)

Another proposal the EPA has issued is the identification of PFOA and PFOS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). CERCLA, better known as Superfund, addresses the cleanup of former sites contaminated by hazardous chemical releases.[22] The establishment of CERCLA specifies standards for waste sites and holds potentially responsible parties accountable for waste releases through cost-recovery action.[23] At the time of its creation in 1980, CERCLA formed a trust fund consisting of taxes from chemical and petroleum industries, which became a vital resource for hundreds of site clean-ups with no identifiable responsible party until funds were exhausted in 2003.[24]

In collaboration with CERCLA, the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) outlines an action plan on how the federal government should dispose of CERCLA hazardous chemical releases and clean up waste sites.[25] PFAS currently reside under the Fifth Unregulated Contaminant Monitoring Rule, which issues a list of unregulated contaminants found in drinking water every five years.[26] If PFOA and PFOS become registered under CERCLA, a more streamlined action plan for PFAS chemical clean-up processes would be implemented, thus preventing continued runoff and widespread contamination of unmonitored and non-operating polluted sites.

Resource Conservation and Recovery Act (RCRA)

In 2021, the Governor of New Mexico, Michelle Lujan Grisham, petitioned the EPA to take prompt action against PFAS contamination and list the chemicals as a class, or as individual per- and polyfluoroalkyl substances under the Resource Conservation and Recovery Act (RCRA).[27] RCRA, similar to CERCLA, provides a framework for the investigation and clean-up of solid non-hazardous and hazardous wastes, however, it instead oversees current waste management at operating facilities.[28] Its large scope encompasses over 3,700 facilities, imposing strict standards for waste treatment, storage, and disposal to minimize the release of contaminants into the ground and surface water, soil, and air, consequently reducing potential adverse health and environmental impacts.[29] In response to Governor Grisham's petition, the EPA acknowledged the threat of unregulated PFAS and outlined its proposal for listing PFOA, PFOS, PFBS, and GenX under RCRA. However, in February of 2024, the EPA amended its initial proposal by expanding its regulation to nine PFAS chemicals, their salts, and structural isomers including PFOS, PFOA, GenX, PFNA, PFDA, PFBA, and PFHxA.[30] If approved, the addition of the nine PFAS chemicals will require facilities to adopt practices that work towards sustainable waste life cycles and prevent further chemical contamination.

State Action

In addition to federal legislation, 22 states have implemented proactive measures to address PFAS in drinking water.[31] States including Maine and New Hampshire have taken action against PFAS contamination by enforcing limitations such as maximum contaminant levels (MCLs) in drinking water and banning firefighting foams containing the chemicals.[32] Establishing MCLs is a critical step in ensuring that drinking water remains safe for consumption, as it establishes clear guidelines for acceptable PFAS levels and prevents the exposure of vulnerable populations to harmful concentrations of these chemicals.[33] Additionally, the prohibition of PFAS in firefighting foams mitigates the release of PFAS in the environment and safeguards the health of firefighters.[34] One of these developments can be seen in Minnesota, which passed a landmark law prohibiting the use of PFAS in any product by 2032, with few exceptions for public health uses.[35] This first-ever U.S. ban on these chemicals is a significant step towards prioritizing environmental sustainability and community well-being. This ban would ideally encourage other states to follow suit; however, it simultaneously highlights the stark contrast between states' actions to combat PFAS pollution. While some states have created proposals and enforced restrictions, others have not taken action on the issues. This discrepancy emphasizes the demand for coordinated and comprehensive action nationwide as well as informing representatives and the public on PFAS contamination to encourage the creation of state legislation.

Currently, the implementation of federal PFAS limitations is critical to protect drinking water and the health of Americans since some states have laws prohibiting any state regulations from being more stringent than federal laws. Six states that restrict the creation of more stringent state environmental laws with no exceptions include Idaho, Iowa, Mississippi, North Carolina, South Dakota, and Wisconsin.[36] Other states have similar provisions with limited exceptions, like Arizona, which prohibits state laws from being more stringent unless there is statutory authority.[37] In contrast, other states have no limitations on state legislation stringency, like California, while others require a cost-benefit analysis or technology feasibility statement for stricter regulations, like New Jersey and Ohio.[38] Previously, Michigan had a No Stricter than Federal law, but the regulation was repealed and signed into law this August, allowing for the creation of state laws that promote better protection of environmental resources.[39] Michigan's actions in light of current events and the federal government's current scope of the waters of the United States (WOTUS) emphasize the need for all states to take action toward safeguarding precious, limited environmental resources. With about half the states passing PFAS legislation and enforcing more stringent laws than federal proposals and the other half of the country creating little to no legislation to address the widespread environmental problem, it poses concerns for public health and unprotected natural resources that transcend state boundaries.

The European Union

The issue of PFAS contamination is not solely found in the United States but has been discovered in surface waters throughout Europe. The contamination in the continent is so widespread that human exposure to the chemicals has amounted to between 52 and 84 billion dollars in annual PFAS health-related costs.[40] In contrast to the United States, the European Union (EU) has taken more coordinated steps in implementing comprehensive proposals to address PFAS environmental and public health concerns. The EU's blanket PFAS ban proposal offers a more comprehensive solution that would be more effective in tackling transboundary pollution in comparison to the U.S., where states have vastly different regulation policies on PFAS. The EU's proposals involve the banning of PFAS in firefighting foams, a significant source of contamination, as well as imposing restrictions on over 10,000 PFAS used across various industries.[41] This regional approach, including the blanket ban, holds several potential benefits, such as preventing companies from merely substituting one PFAS for another unregulated variant and prompting other countries, like the United States, to follow suit by enacting more extensive PFAS regulations to protect citizens' health and the environment. If the United States were to enact similar widespread regulations as proposed by the EU, cohesive policies across states could help facilitate efficient, collaborative efforts to tackle PFAS pollution.

In contrast, the EU's proposals have also sparked discourse concerning the ban's potential repercussions. Critics argue that a complete ban could have unintended consequences for certain industries, including disrupting supply chains and economic activities. Companies heavily reliant on PFAS in their manufacturing processes might face increased production costs, requiring the adoption of alternative technologies.[42] Although these measures may be drastic, they could propel industries to shift to new technologies, creating new jobs and more innovation that contribute towards a more sustainable society.

The PFAS proposals, including the restriction of 10,000 PFAS, were published by the European Union's European Chemical Agency Committee for Socio-Economic Analysis (ECHA) in 2023.[43] If approved by ECHA's committee and the European Commission, the regulations would be incorporated into the European Union's robust Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) framework.[44] REACH aims to ensure the safe use of chemicals within the EU and promote the development and implementation of alternative, less hazardous substances.[45] Additionally, by establishing PFAS under the scope of REACH, the EU can implement streamlined standards for gathering information on hazardous substances, facilitate informed decision-making regarding their use, and regulate these chemicals uniformly.[46] The integration of PFAS into the REACH framework illustrates a comprehensive and large-scale approach to PFAS management, from which the United States could draw inspiration from. However, it is crucial to approach this regulatory challenge by considering the various factors impacted by a blanket ban to ensure these policies can mitigate the harmful effects of PFAS without causing significant disruptions to domestic and global economies.

PFAS Litigation

PFAS Settlements

While significant efforts have been made to address PFAS contamination and hold polluters accountable through new legislative proposals, there has also been a notable increase in PFAS-related lawsuits. In fact, from 2005 to 2022, a staggering number of over 6,400 lawsuits relating to the chemicals were filed.[47] A prominent defendant in these cases is DuPont de Nemours (DuPont), an American chemical company renowned for its manufacturing of building materials, fuels, and various chemicals. DuPont alone has been involved in more than 6,100 of these PFAS cases, indicating the scale of its complicity in PFAS pollution.[48] 3M, another conglomerate, was named in an average of more than three PFAS-related lawsuits a day in 2021.[49] The copious PFAS pollution cases filed necessitated their consolidation into multidistrict litigation, resulting in hundreds of cases being sent to the United States District Court of South Carolina.[50] Multidistrict litigation consolidates pools of resources, expertise, and knowledge of previous PFAS cases to establish a comprehensive understanding of the extent of the chemical's pollution and its extensive consequences.[51]

A multitude of cases against 3M and DuPont include local governments that wanted to recover the costs of polluted water supplies and individuals who have incurred health problems from contamination exposure. In response to overwhelming action taken against conglomerates' use of PFAS, these corporations recently made sizable settlements to compensate for the repercussions of their actions. This past June, chemical companies Chemours, DuPont, and Corteva agreed to resolve PFAS pollution in a class of public water systems.[52] PFAS-contaminated water monitored under the EPA and not owned by the state or federal government will be classified under the settlement of $1.185 billion.[53] Within the same month, 3M agreed to pay $10.3 billion to over 300 plaintiffs, currently the biggest settlement yet against a PFAS manufacturer.[54] 3M's commitment to addressing PFAS contamination did not end with the financial settlement. The company demonstrated a proactive stance by pledging to discontinue its manufacturing of PFAS and inclusion of the chemicals in its products by 2025.[55] The implications of these PFAS settlements have echoed not just within the legal sphere but also resonated in the domains of corporate responsibility and environmental activism, emphasizing the need for corporations to implement health and environmentally conscious practices to prevent widespread harm.

Supreme Court Cases

When the Clean Water Act (CWA) was established in 1972 to regulate discharges of pollutants in aquatic resources, it outlined federal jurisdiction over navigable waters, classifying them under the Waters of the United States (WOTUS).[56] What constitutes as WOTUS and the U.S. government's scope of authority to regulate PFAS and protect waterways has been contested for decades, and were narrowly delineated through recent Supreme Court of the United States (SCOTUS) cases. Section 404 of the Clean Water Act prohibits the discharge or dredging of any filled materials into navigable waters and was a statute that was challenged in *United States v. Riverside Bayview Homes, Inc.* in 1975.[57] In the case, the Supreme Court sided with the United States Army Corps of Engineers, affirming the requirement of permits from landowners before discharging materials into "wetlands adjacent to navigable bodies of water and their tributaries".[58] Subsequent to this case was *Solid Waste Agency of Northern Cook County v. U.S. Army Corps of Engineers* which prohibited the Clean Water Act from extending its jurisdiction to isolated ponds that are not adjacent to open, navigable waters.[59]

Further limiting CWA's authority was *Rapanos v. United States*, a SCOTUS case decided in 2006.[60] The court voted 4-1-4 rejecting the U.S. Army Corps of Engineers' decision to prohibit defendant Jon Rapanos from filling three wetland areas on his property.[61] According to the Supreme Court, the Corps, District Court, and Court of Appeals erred in its interpretation of the CWA and what constitutes as Waters of the United States.[62] In former Justice Scalia's plurality opinion, he asserted that for wetlands to be protected under the CWA, they must consist of a "relatively permanent, standing or flowing" body of water, rather than solely having a "hydrological connection" or featuring an "ephemeral" or "intermittent" flow, as in the case of Rapanos' wetlands.[63] In a separate concurrence, Justice Kennedy disagreed with the plurality opinion's definition of WOTUS, declaring that a wetland must demonstrate more than mere adjacency to a flowing extension of navigable water; instead, it necessitates proof of a significant nexus to a navigable body of water, one that influences the "chemical, physical, and biological integrity" of such navigable waters.[64] Opinions dissenting the plurality emphasized the ramifications of limiting the CWA's authority, explaining how the EPA's broad scope of WOTUS is necessary to eliminate pollution in the country.[65] Seventeen years after *Rapanos v. United States*, the Supreme Court released a decision on *Sackett v. EPA*, further reinforcing the Rapanos plurality as well as concerns about environmental repercussions that may manifest from the reduction in federal agencies' scope.[66]

Sackett v. Environmental Protection Agency (EPA)

In a recent landmark ruling released in May 2023, the Supreme Court delivered its verdict on *Sackett v. EPA*, a case with serious implications for the interpretation and application of the Clean Water Act's WOTUS provisions, and ultimately, for the protection of U.S. waterways. Michael and Chantell Sackett, operators of an excavation company, bought a lot a couple of hundred feet away from Priest Lake, Idaho- a navigable water protected under the Clean Water Act.[67] As the Sacketts began backfilling their lot to build their home, the EPA informed them that their actions were in violation of the CWA since they were filling a protected wetland.[68] The wetlands in question on the Sackett's property were situated "near a ditch that fed into a creek, which fed into Priest Lake", thus establishing a hydrological connection to a navigable water and therefore classifying it as a protected wetland under the CWA.[69] The couple disputed this assertion, arguing that their property did not meet the criteria under WOTUS.[70] In the Supreme Court's contentious decision, all nine Justices ruled in favor of the Sacketts, stating that the EPA did not have the authority to regulate their property, however, there were stark disagreements on how to determine what bodies of water could and should be protected under the Clean Water Act.[71]

The majority opinion delivered by Justice Alito and joined by Justice Thomas, Barrett, Gorsuch, and Roberts, agreed with former Justice Sacalia's definition of WOTUS in Rapanos classifying protected waters as "relatively permanent, standing or continuously flowing bodies of water".[72] They stated the only wetlands protected are ones that are "indistinguishable from waters of the United States", which occurs solely when the respective adjacent wetlands have a continuous surface connection to the waters of the United States.[73] By establishing a more limited scope on the CWA, the Justices dismissed the EPA's argument regarding the adverse ecological consequences of refining the definition of adjacent wetlands.[74] Additionally, Justice Alito rejected former Justice Kennedy's significant nexus rule from Rapanos, stating that only wetlands with a continuous flow to a federally protected water merit protection under the CWA.[75]

Justice Kavanaugh, one of the court's conservative-leaning judges, strongly disagreed with the conservative majority's interpretation of protected wetlands covered by the Clean Water Act, cautioning about the "significant repercussions for water quality and flood control" by removing crucial federal protection of adjacent wetlands.[76] He further elaborated that this shift in the Clean Water Act's jurisdiction from the statutory text overturns decades of EPA implementation and SCOTUS precedent.[77] In both Justice Kagan and Kavanaugh's opinions, they asserted that the majority's examination of the CWA's scope reduces the definition of adjacent wetlands to only waters that are continuous with or border-protected waters and leaves out a crucial part of adjacency.[78] In their opinions, the justices maintained that adjacent wetlands can also include wetlands separated from a covered water source by artificial or natural structures, emphasizing that a mere dike or beach dune does not negate a wetland's adjacency to a navigable waterway.[79]

The verdict in *Sackett v. EPA* has a profound impact on the legal environmental landscape as it serves to clarify the confines of federal jurisdiction under the Clean Water Act, offering a more precise interpretation of what wetlands constitute as a water of the United States. The case was a victory for property rights advocates, allowing for fewer environmental regulations on private property. Additionally, restricting the ability of federal regulatory enforcement on wetlands implements a check on the power of administrative agencies. Contrarily, this SCOTUS decision has upended the framework that has prioritized the protection of U.S. waterways since the 1970s, leaving communities and ecosystems vulnerable to pollution, especially from the widespread presence of PFAS across the nation.[80]

Possible Repercussions of Sackett v. EPA

The shift in federal jurisdiction following *Sackett v. EPA* resulted in rendering millions of acres of wetlands susceptible to discharged unregulated chemicals like PFAS. Wetlands cover over 5.5% of land in the contiguous United States, putting much of the country at risk of unregulated pollution.[81] Wetlands play an invaluable role in helping reduce the effects of climate change and in providing a thriving environment for species.[82] Their ability to absorb additional water and slowly release excess water prevents flooding, in turn mitigating erosion and waterlogging of crops.[83] When these areas are filled by landowners, it reduces the water retention ability of wetlands, a crucial factor in mitigating the effects of climate change.[84] In addition to reducing the absorption of flood water, filling wetlands damages plants and root systems acting as a buffer that traps contaminants and maintains water quality.[85] The damage of this essential barrier allows more pollutants like PFAS to spread via U.S. waterways, which further harm the surrounding biological ecosystems and human health.[86] Moreover, wetlands are homes to a variety of species, providing essential nutrients and habitats for fish and birds as well as breeding and migration grounds.[87] Increased pollution through filling and migration of PFAS into these ecosystems can contribute to bioaccumulation in waterways, crops, and organisms, causing irreparable damage to the biota and successive generations.[88] With the revocation of federal protection over some wetlands, it has become imperative that states implement their own legislation to conserve their natural resources.

Future Propositions

There remains a precarious balance between the powers of the federal and state governments regarding regulations encroaching on citizens' property, especially in the context of environmental regulations. Nevertheless, it is simultaneously pertinent to be cognizant of the citizens and ecosystems left vulnerable when there are inadequate protections against PFAS and landowners' actions. States with barriers to creating stricter laws than federal legislation need to take action to safeguard areas that the Clean Water Act, EPA, and other federal agencies have minimal jurisdiction over. By doing so, states can not only preserve these essential ecosystems but also ensure the long-term well-being of their residents who rely on the wetland's ecological services and organisms that depend on those biospheres for survival.

In similar environmental situations to PFAS where there was an absence of legislation, common law has played a pivotal role in shaping environmental regulation.[89] Both citizens and advocacy groups have turned to the courts as a means of catalyzing change through regulation by litigation when federal regulatory agencies face limitations on enforcing environmental protections.[90] Prior to the EPA and CWA, nuisance and trespass laws were used to take action against pollution that caused damage to public health or invaded property to hold perpetrators responsible and collect damages.[91] These cases have been instrumental in providing crucial means to fill regulatory gaps and advance environmental protection by means of the judicial system. With current multidistrict litigation occurring in the South Carolina district court for PFAS cases, it has led to the creation of new precedents for future PFAS cases to follow while legislative proposals are still in process.

Most environmental laws in the United States have been reactionary, as they have often created laws to mitigate decades-long problems instead of proactively addressing the effects when the problems are more easily manageable. The politicization of environmental protection has further hindered the creation of laws since political parties rarely come together to confront environmental threats until considerable harm has occurred, accompanied by ample scientific evidence confirming the adverse consequences of the lack of government action.[92] While there are other factors to consider before implementing environmental protections and PFAS regulations including possible economic repercussions, environmental legislation should adhere more to the precautionary principle. This principle underscores the importance of taking proactive measures to prioritize public and environmental health in the face of scientific uncertainty.[93] Although it is acknowledged that PFAS have contributed to widespread pollution and a range of health problems in communities and ecosystems nationwide, the full extent of their harm is not fully clear.[94] Despite the lack of complete knowledge, in an era of numerous ecological challenges, it is pertinent for multi-governance initiatives and legislation across parties to prioritize a sustainable, resilient, and equitable future, even when conclusive evidence on per- and polyfluoroalkyl substances is still emerging.

Please scan here to see References.

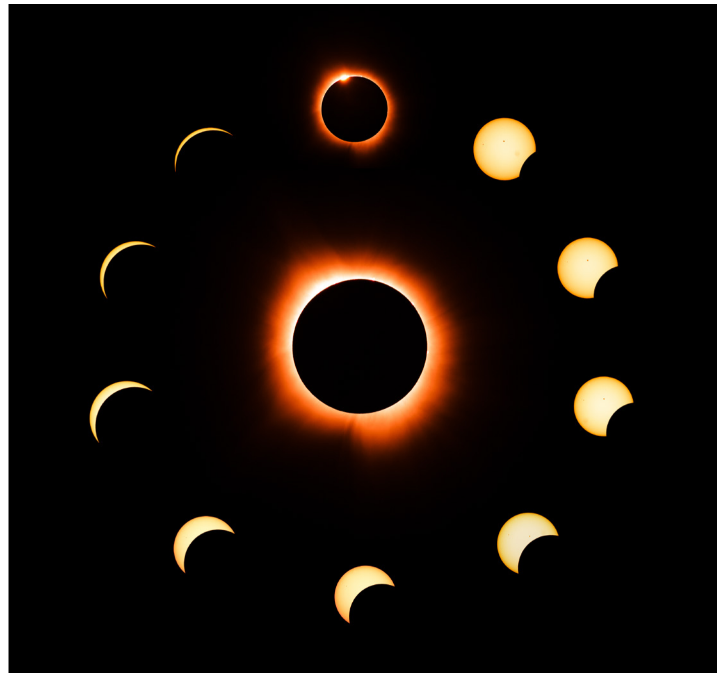
Chasing Totality: 2024 Solar Eclipse

by Tyler Parker

On April 7th, I, along with a group of 49 other students in the Georgia Tech Astronomy club, embarked on a 12 hour bus ride to the Ozark Mountains in Missouri with the sole purpose of seeing this year's total eclipse. The last time an eclipse was able to be viewed in totality in the US was in 2017, and the next time won't be until 2044, so this was an opportunity we couldn't pass up. After spending a cold night at a campsite, we joined hundreds of other people at a nearby park where we watched the sun slowly disappear from view until everything was in total darkness. People yelled and applauded and savored what will be, for some, a once in a lifetime experience, and a little under four minutes later, it was over.

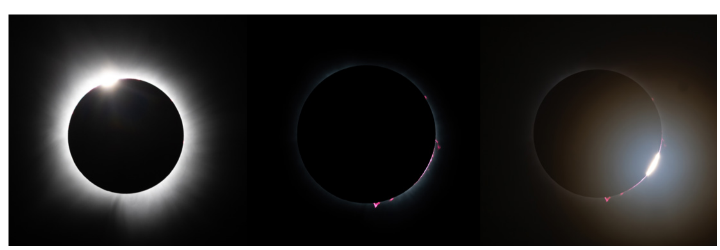
Four minutes of totality is a narrow time frame, but there's a lot that goes into viewing and imaging an eclipse that has to take place beforehand. To view the eclipse safely, most people use glasses specifically designed to reduce light down to levels that is safe to view - specifically no more than 0.00032% of the sun's light can be let through - and then it just becomes a matter of looking up and finding the sun (Weitering, 2019). Taking photos is a little more involved. You need specialized filtering for a camera just like for the eyes, and without it you can actually burn through components in the lens and body because you're effectively concentrating light like you're using a magnifying glass. Because the sun emits light in spectrums like UV that aren't visible, it isn't enough to just have a dark filter, you need one specifically designed for the sun. Most solar filters are ND 100000, meaning they only transmit 0.5^{999998} percent of the light that enters. Once you have the filter in place, then it becomes a matter of tracking the sun as it moves across the sky. To our eyes, the sun appears to move very little over the course of that 4 minutes, but when you're zooming in 20x or more, that slight movement becomes very noticeable. Some people use specific equatorial mounts, that use polar alignment to slowly move the camera to account for the rotation of the earth and stay focused on the right point, while others just manually adjust over time. It seems pretty easy, but with the pressure of time it can actually become a stressful task.

When viewing the eclipse, there's a few main features that people look for and try to photograph. The corona is a white cloud of plasma that radiates out from the sun, and is a prominent feature in virtually any photo you will see during totality. The beautiful visual effect we see during the eclipse happens when sunlight is scattered by electrons in the corona (Woo). The higher the density of electrons, the brighter the corona appears, which is why it looks wispy and becomes dimmer as it gets further out. The shape of the corona is affected by magnetic fields in the force of the sun and can cause some interesting and noticeable features such as loops and plumes of light (NASA, 2024). The chromosphere is a region of reddish-pink plasma between the surface and the corona, with jets and rings of plasma projecting off it called prominences. These cannot be viewed by normal



cameras or the human eye except during totality, because normally the light from the sun completely overwhelms them. The cause of prominences are largely unknown, but are theorized to be caused by magnetic activity and can extend hundreds of thousands of kilometers above the chromosphere (Britannica, 2024). The Diamond Ring and Bailey's Beads are both effects that occur at the very beginning and end of totality, where the sun barely peeking out from the moon creates some incredibly interesting shapes that have become iconic. Photographing these different parts of the suns requires a variety of exposures and very good timing, but the results can be absolutely incredible.

The journey to see totality was one that, despite the almost 27 hours of time spent on a bus, was completely worth taking. There's something about that experience that cannot be fully conveyed using words, and if you get the chance to travel to Europe for the next one in 2026, or wait until 2044, take it, because it is something you will never forget.



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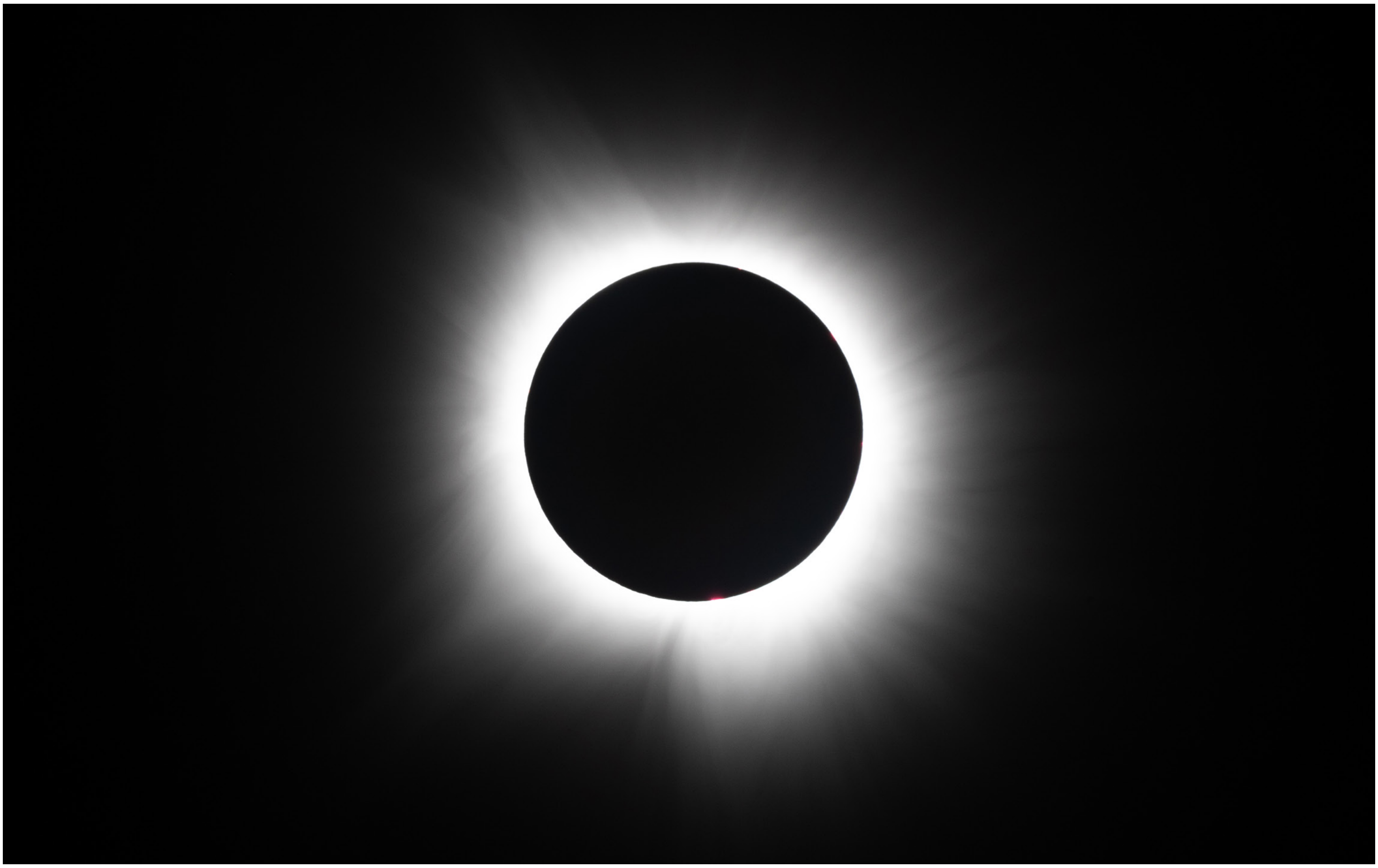
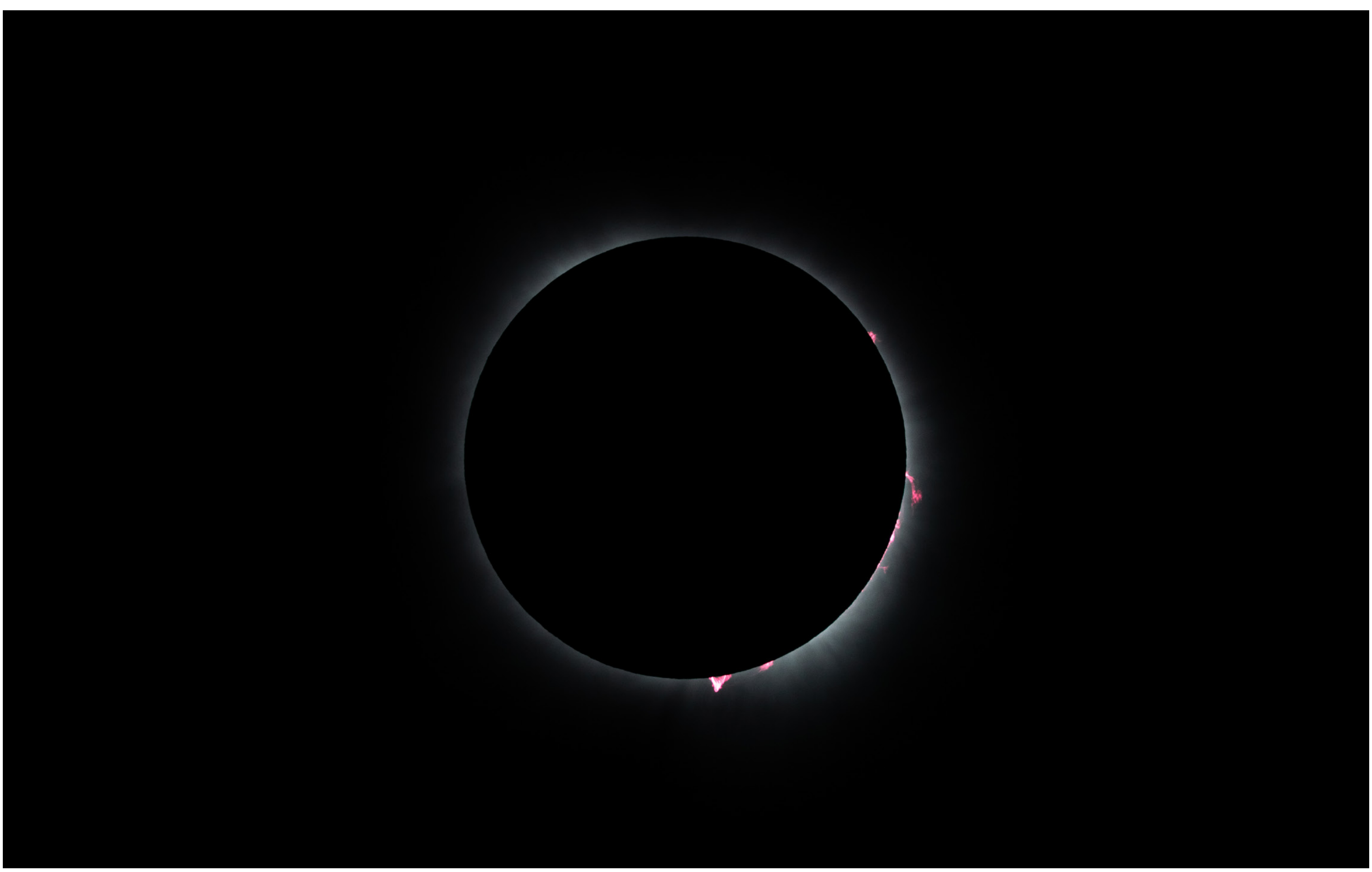
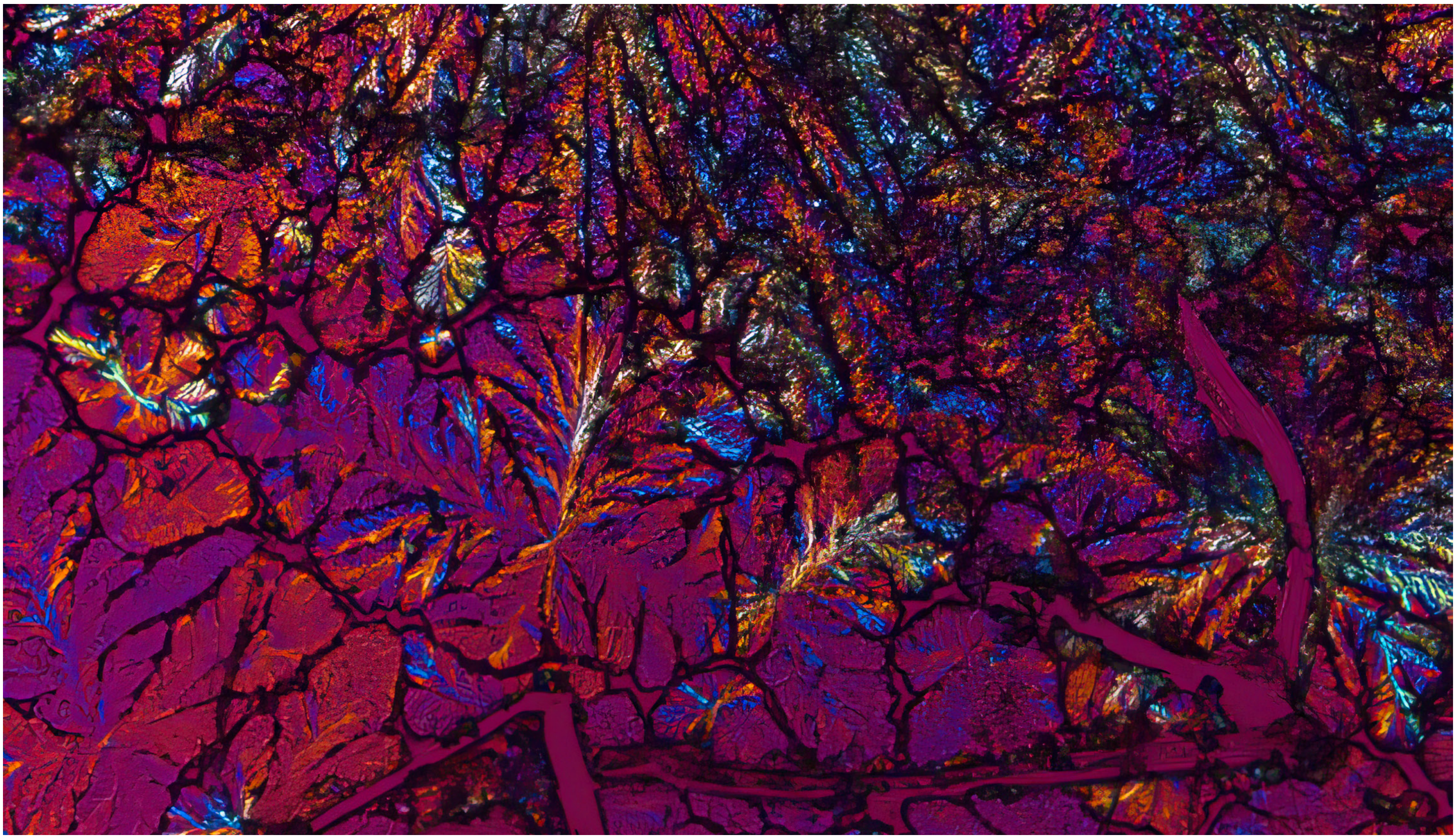




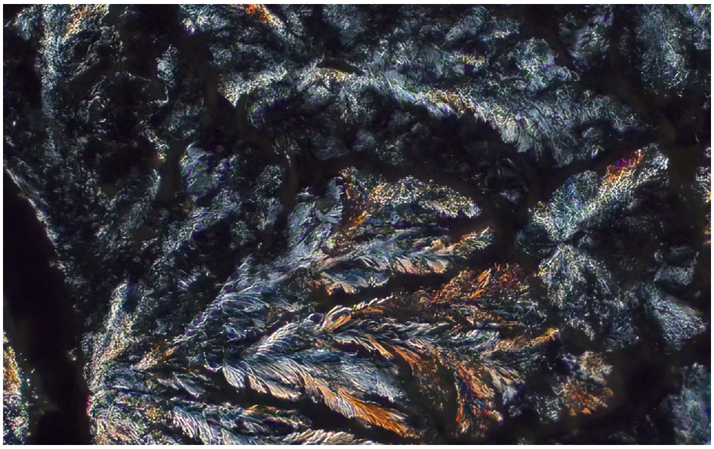


Semi-Crystalline Polymer Films

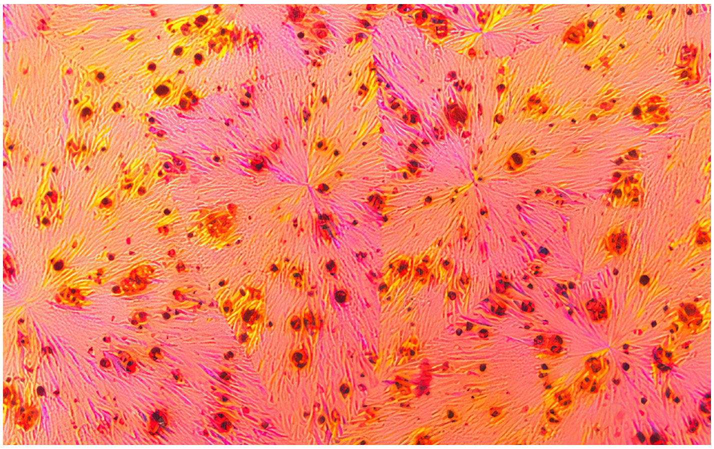
by Reanna Rafiq[1]

All the images found at the start of each article are of various polyethylene oxide (PEO) films. PEO is a very common polymer used in various applications ranging from adhesives to solid-state batteries. It is highly crystalline and is quite soluble in a variety of solvents, including water and multiple types of organics.

Samples are imaged with a Leica microscope with cross-polarized light at a 90° angle at various magnifications in conjunction with a phase plate to provide color to an otherwise transparent film, and thus enhance its crystalline structures. These structures introduce interference patterns that manifest as differences in both color and intensity.



In the image above, 5 weight percent of PEO was dissolved in cyclohexanone and heated at 105 °C. The solution was then dropcast onto a glass substrate. This solution was one out of a series of blends intended to be used as soft organic mixed ion-electron conductors (OMIECs). These blends contained varying ratios of PEO, a known ion conductor, with P3HT or POT-co-DOT, known electron conductors. Soft OMIECs can be used in many energy storage applications, including solar cells, batteries, and supercapacitors. They are also used in biomedical applications, where thin layers are often useful to make flexible conductive products. While these materials have very tunable properties and can conduct both ions and electrons, researchers still have many obstacles to overcome regarding their stability in various environments and long-term usage potential.



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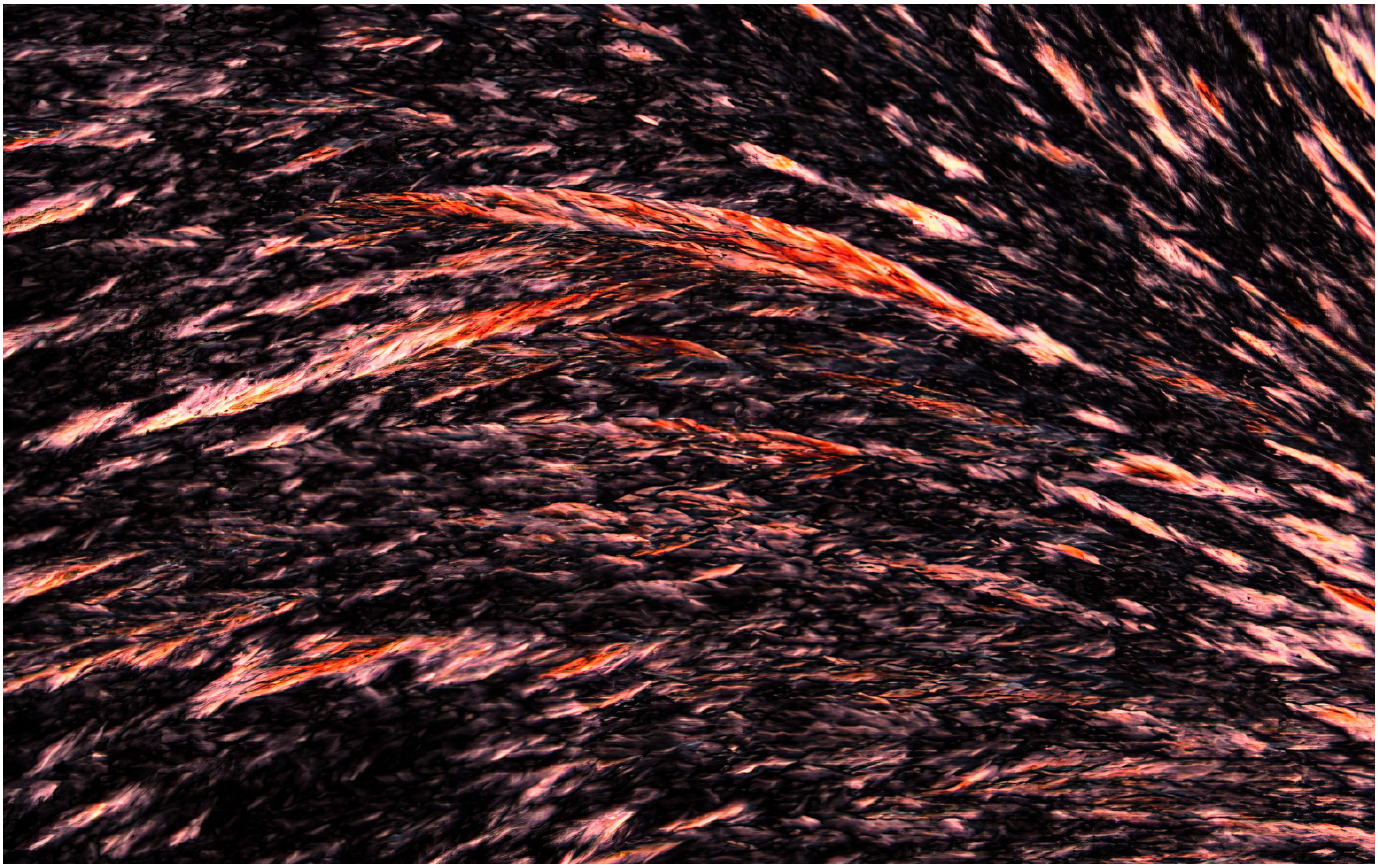

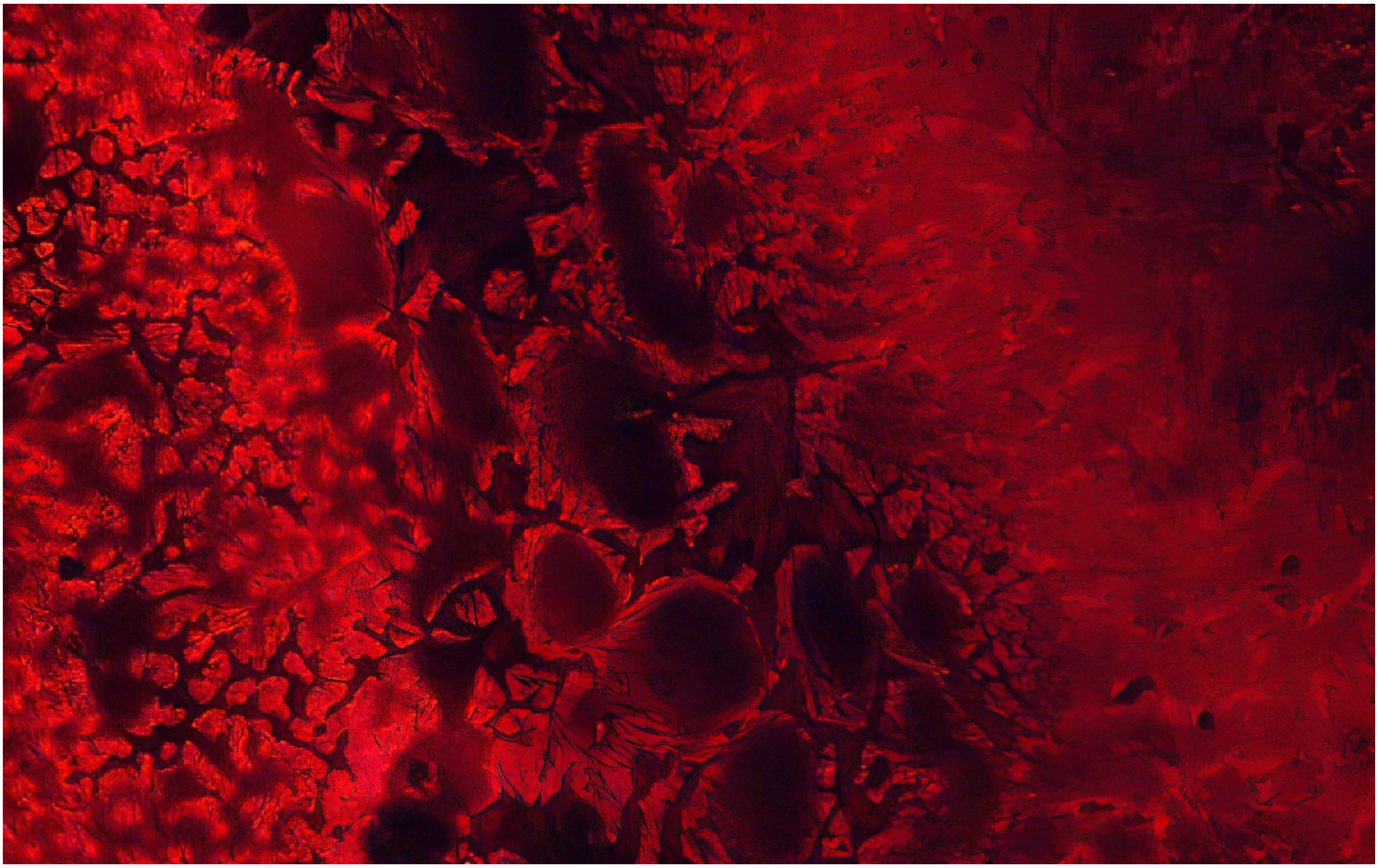


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Exploring the Controlled Release Dynamics of Immunoglobulin G from Hydrogel Encapsulation: Insights into Drug Delivery Kinetics

Xi Ying[1], Xinyi Sheng[1], Wenting Shi[1], M.G. Finn[1]

My name is Xi Ying, and I am a third-year biochemistry major undergraduate student currently conducting research as an undergraduate research assistant in Prof. M.G. Finn's lab. As an emerging researcher deeply engaged in the exploration of drug delivery mechanisms, my academic journey has been marked by a commitment to understanding the intricacies of hydrogel-based systems for controlled therapeutic release. My undergraduate work at the Georgia Institute of Technology has afforded me the opportunity to delve into the complexities of immunoglobulin dynamics within novel hydrogel matrices, contributing to the advancement of sustained drug delivery technologies. Upon entering a Ph.D. program in the near future, I aspire to transition into the industry, where I can apply my expertise and continue to innovate in the field of drug delivery systems. I am particularly drawn to the challenges and opportunities in organic chemistry. This alignment of my academic focus with industry objectives underscores a professional goal to bring scientific discoveries from the bench to practical application.

Acknowledgements

I wish to extend heartfelt thanks to my graduate student mentor Wenting Shi for her invaluable guidance, and to my lab partner Xinyi Sheng for her unwavering support and collaboration. Special thanks to my research advisor, Prof. M.G. Finn, for his inspiring direction and profound impact on my research journey. This project would not have been possible without his help.

Abstract

Monoclonal antibodies have revolutionized treatment paradigms across a range of diseases due to their specificity and efficacy. However, their therapeutic potential is often limited by conventional delivery methods, leading to suboptimal dosing and increased side effects. This study introduces an approach to control the release kinetics of Immunoglobulin G (IgG) through hydrogel degradation, proposing a promising strategy for improving drug efficacy and patient compliance while reducing adverse effects. We investigate the use of oxanorbornadiene (OND)-modified dextran hydrogels, utilizing the ester hydrolysis and retro-Diels-Alder (rDA) mechanism for programmable gel degradation, which leads to highly tunable release profiles. Our findings suggest that IgG release kinetics can be meticulously controlled by the degree of substitution (DS) in OND-dextran complexes, polymer weight percentages, and polymer chain lengths. These insights contribute to the design of drug delivery systems with programmable dosing profiles. Preliminary results indicate that IgG can be released sustainably for up to three weeks, demonstrating both traditional first-order and intriguing non-first-order release kinetics. This work highlights the potential of hydrogel-based platforms in patient-centric therapy and presents a novel method for the programmable delivery of monoclonal antibodies.

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Introduction

The rise of antibody-based drug system

During the last 30 years, antibody therapy for targeted diseases has emerged as one of the most efficient therapeutic strategies. Antibodies, unlike antibiotics, are produced within a living body. They play an important role in the body's immune system by fighting bacteria and antigens. Antibodies can be produced within the body exclusively by B-cells, comprising different sequences of amino acids, or they can be laboratory-synthesized to enhance or restore immune response.[8] Although antibodies are produced in billions of forms, they can be differentiated by their unique antigen-binding sites. Laboratory-synthesized antibodies, known as monoclonal antibodies (mAbs), are engineered to target specific antigens and initiate immune pathways to eliminate them. For example, they can flag cancer cells, inhibit essential pathways for cancer cell growth, and promote cell apoptosis. In 1975, Dr. César Milstein and Dr. Georges Köhler developed the technique for mass production of monoclonal antibodies through hybridoma technology. Their groundbreaking work enabled the production of specific antibodies in large-scale cultures, significantly advancing the use of antibodies in medical and industrial fields. Their pioneering study earned them the Nobel Prize in Physiology or Medicine in 1984. Since then, large-scale manufacturing production of mAbs for clinical application has been combined with recombinant DNA technology or with drug delivery devices for the prevention and cure of immune disorders.[1]

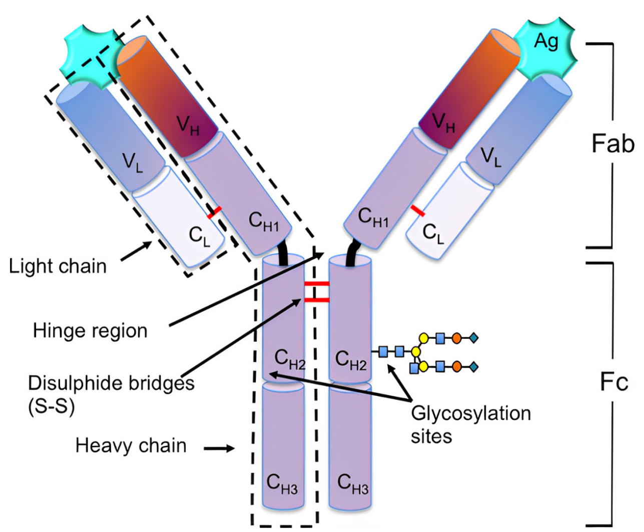


Figure 1. Structural diagram of IgG. The Fc region plays a pivotal role in mediating immune system effector functions and interactions with Protein-A and -G. Key abbreviations include Fab (fragment antigen binding), Fc (fragment crystallizable), IgG (immunoglobulin G), and Ag (antigen).[2]

Antibodies come in many shapes and sizes; the Y-shaped molecules (Figure 1) are identified as immunoglobulin G (IgG), which has a structure comprising four polypeptide chains – two heavy (50 kDa) and two light chains (25 kDa) – linked by noncovalent bonds and disulfide bridges. The primary components of antibodies are the antigen-binding (Fab) and fragment-crystallizable (Fc) regions. The Fab region includes variable heavy (VH) and variable light (VL) regions, while the Fc portion, crucial for immune signaling and effector functions, consists of constant heavy (CH1, CH2, and CH3) regions.[2]

Hydrogel as Drug Delivery System

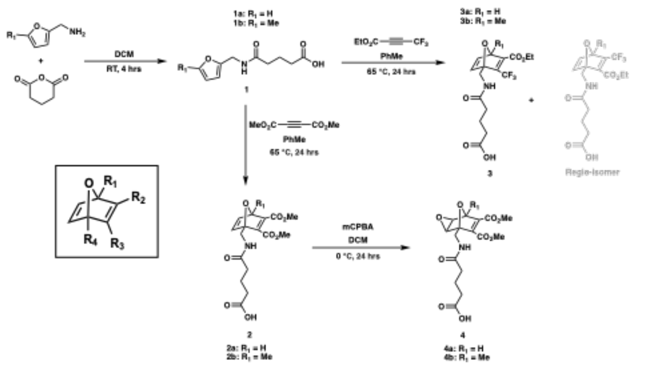
The drug delivery system encompasses technologies designed to facilitate the absorption, transport, and elimination of drugs within the body.[9] In this study, we focus on the sustained release method, a specialized drug delivery system. This approach, known for its minimally invasive measures, has demonstrated improvements in drug efficacy, patient adherence, and a reduction in side effects. In applications such as cell-based therapies and protein delivery, the controlled degradation of hydrogels serves a dual purpose by regulating the release rate of the administered substance and facilitating the removal of the device from the body once its function is no longer required.[3]

Compared to other systems like microneedles or certain microparticles, optimizing the cargo release profile in hydrogel platforms is intricate, and many such depots suffer from an uncontrolled initial burst release. To tackle this, we employed oxanorbornadiene (OND) linkages, which react with thiol nucleophiles to trigger bond cleavage by retro-Diels Alder (rDA) fragmentation with half-lives ranging from minutes to months. Our previous studies involved the fabrication of hydrogels using OND-modified dextran (dextran-OND) and multivalent polyethylene glycol thiols (PEG-SH), prepared in a physiological buffer suitable for injection. We entrapped virus-like particles (VLPs) as models for nanoparticle vaccine candidates. We found that VLP cargo demonstrated loading capacities into the gel exceeding 90%. The release pattern of VLPs was programmable, showcasing burst, linear, positive exponential, and delayed profiles for up to three weeks. Building upon the observed profiles for VLPs, our current study seeks to establish a diverse in vitro release profile of IgG, a much smaller protein.

Preliminary data

OND synthesis

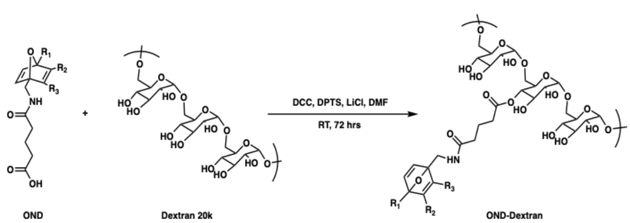
The precursor Furan 1 was synthesized using commercially available furfurylamine molecules and glutaric anhydride in DCM; OND series were then synthesized using the precursor Furan 1. In Scheme 1 below, the synthetic route for each OND is displayed.



Scheme 1. Reaction scheme of different ONDs. OND 3 contains two regio-isomers (the major product is shown in dark color and the minor product is shown in light color). Unlike OND 2 and 3, OND 4 was found to be non-fragmentable, indicating that the retro-Diels Alder (rDA) reaction does not occur. The boxed structure displays the overall structural format of OND products.

OND-Dextran Synthesis and DS Calculation

After synthesizing ONDs, we functionalized dextran with ONDs via esterification as shown in Scheme 2. Then, we generated a correlation graph to determine the change in the degree of substitution (DS) in OND-dextran complexes by various reagent factors. It was found that the DS is closely related to two factors - OND/dextran ratio and N,N'-Dicyclohexylcarbodiimide (DCC). We found that the higher the OND/dextran ratio and the higher amount of DCC, the higher the DS values, which indicate a larger amount of OND attached per 100 dextran units. For example, if the DS is 15%, then 15 ONDs are linked randomly within 100 sugar units (Figure 2). In response to increasing OND/dextran ratio and/or DCC, we were able to achieve DS up to 31%.



Scheme 2. Dextran modification reaction. Dextran is modified with OND, and the reaction conditions are proposed.

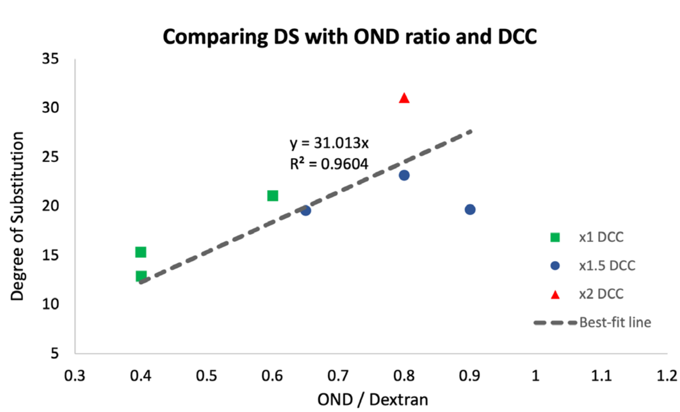


Figure 2. DS correlation with OND/dextran ratio and DCC content.

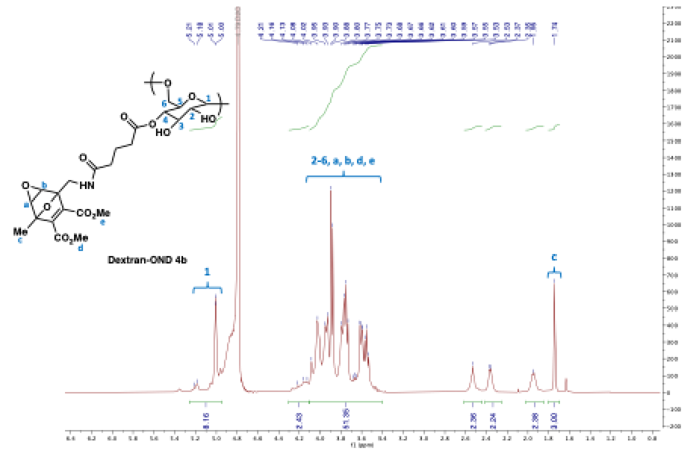


Figure 3. H NMR spectrum of OND 4b-dextran.[1]

Equation 1 calculates the % DS value from the integration of proton peaks in the NMR spectrum, where H indicates the area under the peak.

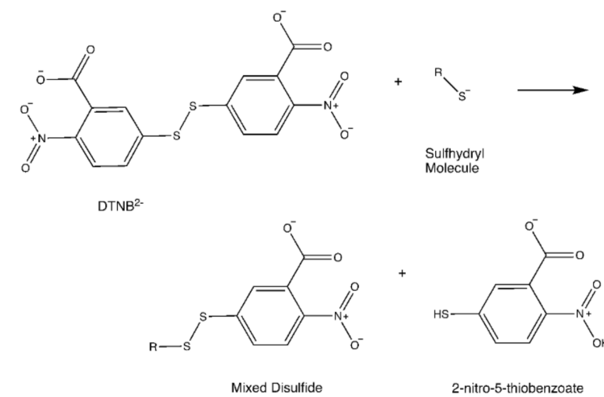
$$DS = \frac{\frac{1}{3}\int Hc}{\frac{1}{6}\int H2-6,a,b,d,e - \int Ha,b,d,e} * 100\% \qquad (1)$$

Equation 1. The % DS value from the integration of proton peaks in the NMR spectrum in Figure 3 gives a DS of 14%.

Importance of PEG-SH and Ellman's Assay

Polyethylene glycol-thiols (PEG-SH) are used to react with the OND-dextran synthesized above to create a three-dimensional network of polymers, resulting in the formation of a hydrogel. The "SH" in PEG-SH stands for thiol, which is a functional group containing a sulfur and a hydrogen atom. The thiol groups in PEG-SH can undergo a chemical reaction with another thiol or with a vinyl group, forming strong covalent bonds. In hydrogel formation, PEG-SH reacts with OND-containing vinyl groups (C=C) at the R_2 site, leading to the chemical crosslinking of polymer chains. This crosslinking imparts structural integrity to the hydrogel, giving it the ability to retain water. The PEG crosslinking length and the active amount of thiol also play an important role in determining the length of drug release.

The number of active thiols is determined through Ellman's Assay. Ellman's Assay is a common biochemical tool for quantifying sulfuryl groups in a sample using a thiol-sensitive tool, DNTB. DTNB, commonly known as Ellman's reagent, is a compound (5,5'-dithio-bis-(2-nitrobenzoic acid)) utilized to measure free sulfhydryl groups in a solution. Upon reacting with sulfhydryl groups, the compound produces a yellow-colored product, which can be quantified using a spectrophotometer due to its significant absorbance at 412 nm.[6] Due to its aromatic disulfide structure and a higher standard oxidation-reduction potential compared to aliphatic analogs, it undergoes an exchange reaction with aliphatic thiols. This reaction leads to the formation of a mixed disulfide and 2-nitro-5-thiobenzoate (Scheme 3).



Scheme 3. Ellman's Assay reaction. Ellman's reagent reacts with sulfhydryl molecule (-SH) on PEG.

The measured absorbance of 4arm-PEG-SH is obtained (Figure 4). By using the best fit equation generated by Microsoft Excel, the cysteine or thiol concentration in the PEG batch can be determined. With a linearity of 0.9999, the equation provided by the linear regression is good for our estimation.

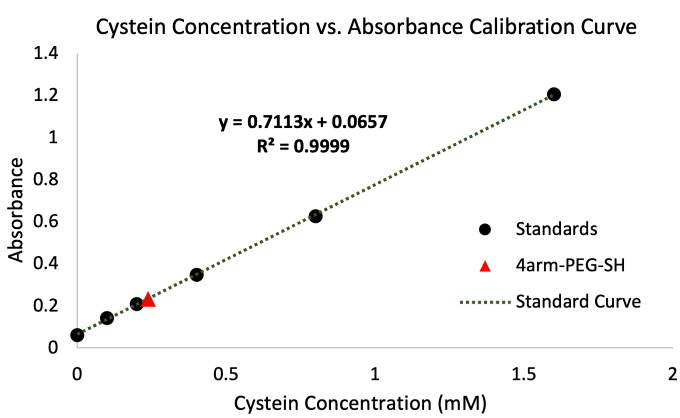


Figure 4. Quantification of sulfhydryl groups 4arm-PEG-SH solution compared to a standard curve at absorbance 412nm.

By calculating the cysteine concentration, or (x), obtained by absorbance using an absorbance plate reader, the number of active thiol groups in 4arm-PEG-SH was confidently calculated as 95%. Applying the same principle, the number of active SH groups in linear 'short-PEG' linkers, another class of crosslinking agents tested in the hydrogels, was measured as 65%.

Putting It All Together

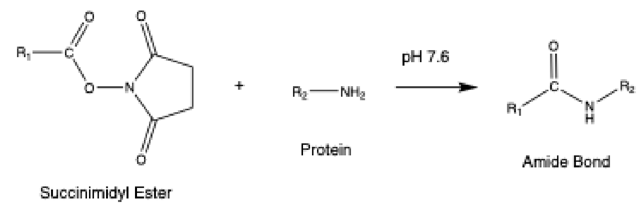
Now that OND 4b and OND 4b-dextran$_{20k}$ have been synthesized and active thiol groups on the PEG-thiol are measured using Ellman's Assay, all required materials for IgG entrapment experiment are collected, the hydrogel can then be fabricated.

Strategies

Fluorescent-Labeling Antibodies for Visualization

Fluorescently labeled antibodies are crucial tools in biomedical research, enabling the detection of antibodies, antigens, and various proteins within cells and tissues. In our experiment, we tagged mouse IgG isotype control with Cyanine 647 blue dye, enhancing our ability to track cargo release over time by measuring the drug release in PBS buffer at pH 7.4.

The investigation is conducted by tagging IgG with light-sensitive Cyanine 647 Succinimidyl Ester to visualize and measure the number of cargo-dye molecules released. This fluorescent dye excites at 647nm and emits light at 665nm. Because IgG contains amine groups on over 80 lysine residues, amine groups are abundant on the surface of IgG.[4]



Scheme 4. Reaction scheme of different ONDs. OND 3 contains two regio-iNHS-Ester reaction scheme of succinimidyl dye with protein in buffer at pH 7.6. This reaction occurs when the primary amine on the protein, in our case IgG, forms an amide bond.[5]

The dye and the protein are mixed in equimolar amounts, maintaining a 1:1 molar ratio. The reaction is allowed to proceed for 2 hours. Following this, a buffer exchange is performed to remove any unreacted dye. This is done by adding fresh buffer to the reaction mixture and centrifuging at 6000 rpm for 15 minutes. The supernatant is discarded, and the pellet is resuspended in fresh buffer. This washing step is repeated three times to ensure complete removal of unbound dye.

Hydrogel Fabrication

We started to make hydrogels using OND 4b-dextran and 4arm-PEG5k-SH, where OND 4b does not undergo retro Diels-Alder fragmentation. Instead, the ester hydrolysis of the OND-dextran interaction site facilitates gel network degradation, releasing the encapsulated cargo. The OND-dextran and PEG-SH materials (in a 1:1 ratio of OND and SH) were separately dissolved in IgG-containing PBS buffer, forming a 10 wt% gel in 100 μL size. The inversion test characterized the gel formation and gelation speed. Three replicates were conducted for each formulation condition.

To compare the effect of the length of PEG-SH crosslinkers and polymer wt% on cargo release, we tested another gel formulation using ultra-short 2arm-PEG-SH linkers with a molecular weight of 200 Da, containing only two repeating units, and increased the polymer weight percent to 20 wt%. This condition was compared with 5000 Da 4arm-PEG-SH. Theoretically, because 2arm-PEG-SH is shorter, the release time would overall increase due to a smaller mesh size, and since more polymer is dissolved in the PBS solution, making a 20 wt%, a more condensed gel will form.

Initial IgG Release Results

As shown in the black curves in Figure 5, when the hydrogel is formulated with a polymer concentration of 10% OND 4b and 4-arm PEG-SH, the observed release kinetics follow a first-order diffusion pattern. This is characterized by a substantial initial burst within the first 24 hours, followed by a progressive decline in the rate of release. Over time, this rate is expected to stabilize, leading to a plateau in the release curve, although this is not depicted in the provided figures. As the DS increases, the release curve shifts to the right, suggesting that the drug is released more slowly. Specifically, when comparing the DS values of 15% and 31%, there is a noticeable difference in the release rate. On the second day, while the gel with a DS=15% has released 50% of its cargo, the gel with a DS=31% has only released 35% of its cargo. This represents a 15-percentage point decrease, which is a 30% reduction in the amount of cargo released relative to the DS=15%.

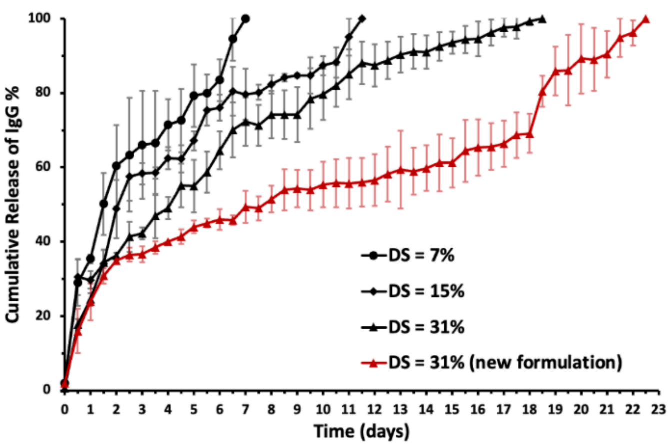


Figure 5. IgG release curve comparing various DS and polymer wt% (black curves) and the red curve measuring weight percent at 20% using ultra-short PEG linkers.

In contrast, when the polymer concentration was increased to 20 wt% and using much shorter PEG-SH linkers—as shown by the red curve in the graph—a more extended-release period is observed. This implies that the higher polymer concentration slows down the release of the drug, likely due to a denser hydrogel network that restricts the diffusion of the drug molecules. Additionally, the red curve shows linear-like IgG release after day 2 instead of first-order diffusion kinetics; this is likely due to the much smaller mesh size of the hydrogels resulting from the ultra-short PEG-SH linkers.

Discussion

In our analysis of crosslinking density, the data indicated that the hydrogel corresponding to the higher DS, higher weight percentage, and shorter PEG chains indicates a higher degree of crosslinking (DC), which implies a more robust hydrogel matrix with a denser mesh. It, in turn, suggests that the release of the encapsulated IgG could be more restrained due to the tighter network of polymer chains (as detailed in Figure 6).

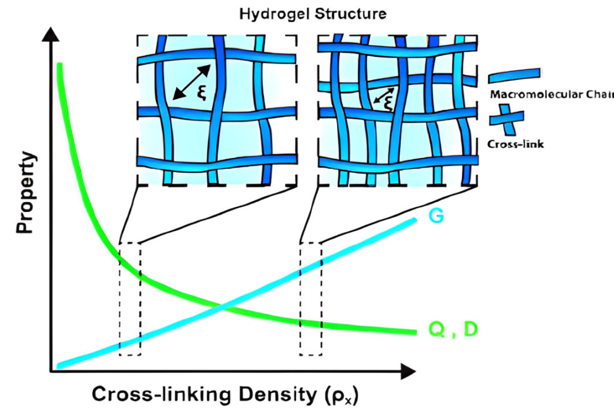


Figure 6. Hydrogel structure relationship with cross-linking density.[7]

Our findings highlight the critical role of the degree of substitution (DS) in OND-dextran complexes in modulating the release rates of encapsulated IgG. From the data above, we have achieved the release of antibodies for up to three weeks by adjusting the weight percent of polymer used in gel fabrication. When tweaking the weight percent of polymer and the molecular weight of PEG-SH, we see a significant decrease in the initial cargo burst. This underscores the potential of chemical modifications in designing versatile drug delivery platforms capable of addressing diverse therapeutic needs.

Furthermore, the comparison of different DS levels and the investigation into the effects of polymer weight percent on cargo release behavior have illuminated the complex interplay between hydrogel composition and drug release dynamics. The significant decrease in the initial burst release with increased crosslinking density points to the potential of optimizing hydrogel formulations for more predictable and controlled drug delivery outcomes.

Conclusion

Our investigation into the controlled release of IgG from hydrogel encapsulations has demonstrated the feasibility of using OND-modified dextran hydrogels to achieve tunable release profiles and provided valuable insights into the optimization of hydrogel-based drug delivery systems. This approach enabled us to engineer hydrogels capable of controlled release, ranging from first-order release to more sustained release patterns over time. This study highlights the significance of crosslinking in influencing hydrogel structure and drug release behavior, offering valuable insights into the design of hydrogel drug delivery systems that can precisely control drug release kinetics. Further research is encouraged to explore the broad applicability of this approach in delivering a variety of therapeutic agents, paving the way for innovative treatments in targeted therapy and beyond.

Future Studies

Studies in the future will aim to broaden the scope of these hydrogel-based drug delivery systems, employing other rDA-based OND molecules and extending their application to a diverse range of therapeutic agents beyond Immunoglobulin

G (IgG). Initial efforts will delve into the exploration of varied hydrogel compositions (using OND 2 and 3) to understand their impact on the release mechanisms of different drug classes, such as small molecule drugs, peptides, and various antibodies. Concurrently, there will be a strong emphasis on enhancing the biocompatibility and biodegradability of these hydrogels, with the goal of mitigating potential adverse effects and ensuring their safe use over extended treatment periods.

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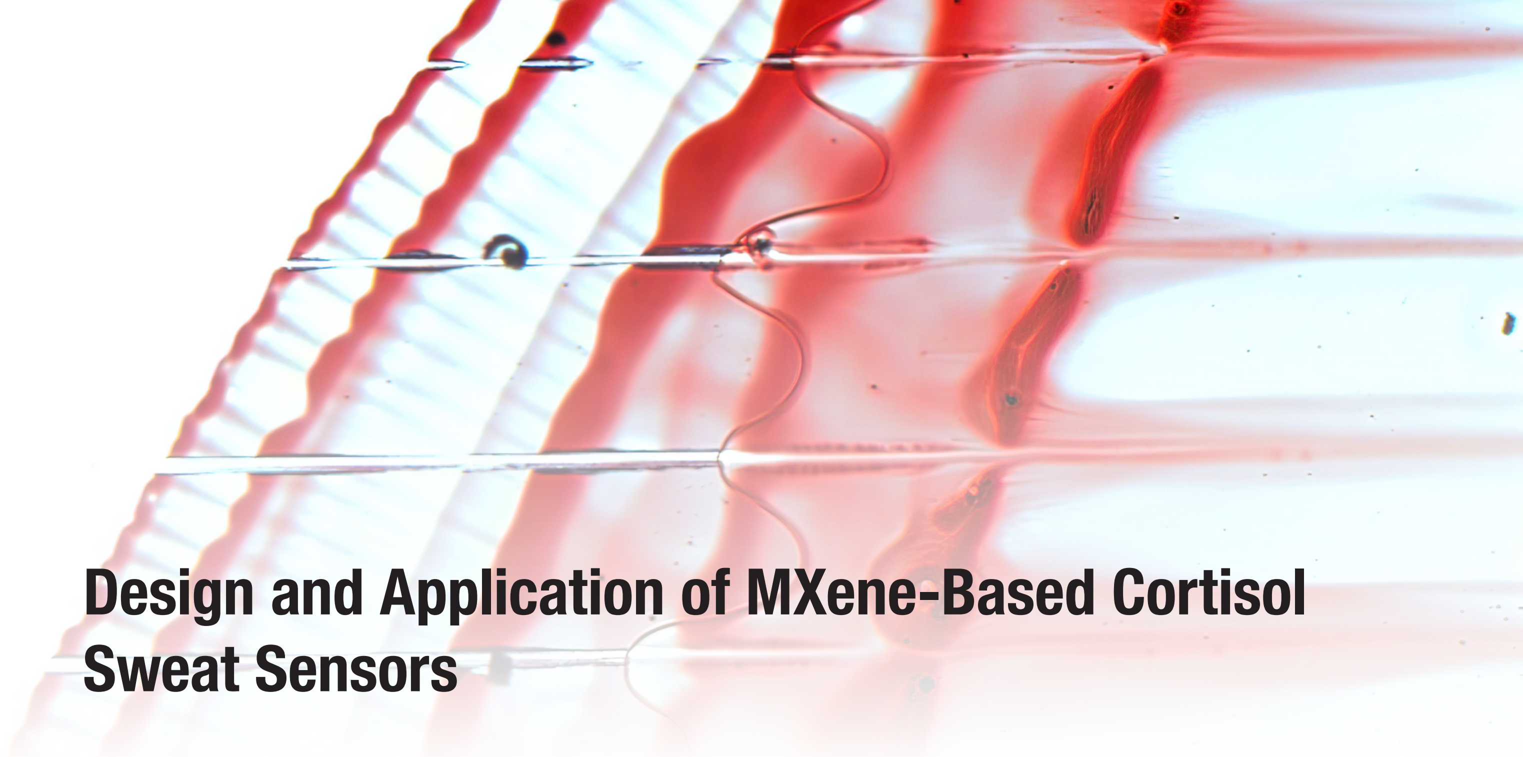

Design and Application of MXene-Based Cortisol Sweat Sensors

Samadhi L. Attanayaka[1]

Samadhi Attanayaka is a first-year biomedical engineering student at Georgia Tech, specializing in the Pre-Health track. Hailing from Kalamazoo, MI, she embarked on her research journey as a junior in high school under the mentorship of Prof. Massood Atashbar at Western Michigan University. Currently, she is further honing her skills under the guidance of Prof. David Myers and the Sensors for Living Systems at Emory University. With a keen interest in surgery, Samadhi aspires to leverage her burgeoning expertise to innovate in the field of biomedical sensors and delve deeper into clinical research. Her dedication to advancing medical technology underscores her commitment to making meaningful contributions to healthcare.

Acknowledgements

I would like to thank my mentor, Professor Massood Atashbar, Dinesh Maddipatla, and graduate students, H. R. K. M. Emani and Alimohammad Haji Adineh for their time, mentorship, and support in making this project feasible. Additionally, I would like to thank Professor David Myers and the Sensors for Living Systems Lab for their support and encouragement thus far during my time at Georgia Tech.

Abstract

This research introduces MXenes, a family of 2D transition metal carbides, nitrides, and carbonitrides, with unique properties for nanotechnology applications. Traditional MXene synthesis using hydrofluoric acid (HF) is inefficient and environmentally harmful. However, the Lewis Acidic Etching Method offers a more efficient and eco-friendlier alternative. The study outlines the synthesis process and incorporation of MXenes into a cortisol sweat sensor for real-time monitoring of cortisol levels in healthcare and stress management. Experimental results demonstrate high accuracy in detecting cortisol levels, though challenges such as sensor reproducibility and material degradation are identified. This work contributes to the development of advanced sensors for personalized healthcare. Future efforts will focus on optimizing sensor stability and commercialization for widespread use.

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An Introduction to MXenes and the Lewis Acidic Etching Process

Unique properties in nanomaterials can come from their thickness, degree of strength, electrical conductivity, and ability to withstand intense heat, allowing ultrathin materials, such as graphene nanoplatelets, to pose immense potential for future nanotechnology (Berger).

MXenes ($Ti_3C_2T_x$) are a prevalent experimental 2D material found in 2011 (Naguib et al.). MXenes consist of 2D transition metal carbides, nitrides, and carbonitrides synthesized through selectively etching MAX phases (Naguib et al.). These phases form a large family of ternary carbides and follow a general formula of $M_{n+1}AX_n$. In this equation, *n* ranges from 1 to 3, 'M' is an early transition metal, 'A' is a group-A element, and 'X' is either carbon or nitrogen, as seen in Figure 1.

The material carries unique conductive and flexible properties allowing various applications from wearable sensors to lithium-ion batteries due to its ability to act as a ceramic and a metal. MXenes are carved from a MAX phase (Ti_3SiC_2) by chemically etching out the 'A' layer of the MAX phase to produce $M_{n+1}X_nT_x$. The general MXene synthesis method uses hydrofluoric acid (HF) as an etchant, but the procedure is inefficient, harmful, and yields excessive amounts of material wastage, resulting in a smaller quantity of MXene synthesized for use. A recent study described a new process, Lewis Acidic Etching, to obtain MXenes without using HF as an etchant (Li et al.). This new procedure makes it less environmentally damaging and less time-consuming. By applying the developed MXenes into applicable settings like lithium-ion batteries, Lewis Acidic Etching is a potential candidate for a more efficient process of MXene synthesis.

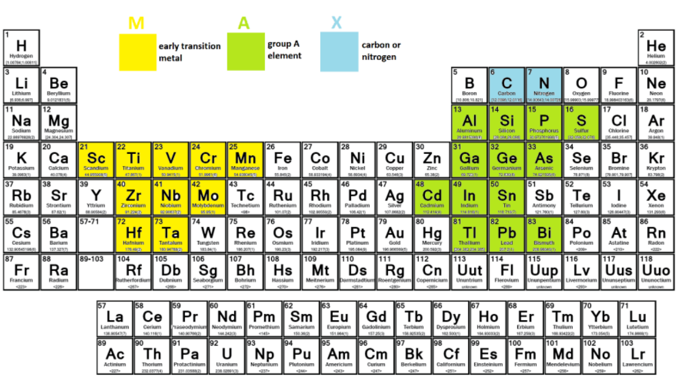

Figure 1. MAX Phase Element Location on the Periodic Table of Elements

Today, over 60 different MXenes have been found through experimentation

The first MXene, titanium carbide ($Ti_3C_2T_x$), was discovered at Drexel University in 2011 after chemically etching the A-layer of the MAX phase (Naguib et al.). This process produced two-dimensional flakes with a general formula of $M_{n+1}X_nT_x$. In this equation, *T* stands for surface functional groups, or termination, which includes fluorine (F), hydroxyl (OH), or oxygen (O) atoms, and *n* ranges from 1-3. Thus, MXenes are a family of 2D crystalline materials with theoretically infinite lateral dimensions with widths of just a few atoms. The terminations display various unique properties that can vary during the etching process.

Due to these terminations and their thin-layered structure, MXenes tend to kink and delaminate during deformation due to mechanical stress to exhibit properties that indicate a medium between metals and ceramics (Berger). MXenes can conduct heat and electricity equivalent to metals, but like ceramics, they are elastically stiff, strong, brittle, and heat tolerant. These properties allow MXenes to be readily machinable and resistant to chemical attacks, thermal shocks, damage, and sometimes fatigue, creep (i.e., a material science concept that describes the likelihood of a material deforming under an applied force of mechanical stress), and oxidation (Linkoping University).

Due to their promise in the future of nanotechnology and their novelty, there are copious possibilities to produce MXene combinations (Drexel University).

Application of MXenes

MXenes are widely researched for applications in biomedical engineering issues. For energy storage, such as Li-ion batteries, the electron movement from the transition metal layer to the electrode produces a high charging rate capability (McDonald). Both wearable physical and chemical sensors are successfully synthesized due to their electromagnetic and elasticity (Xin et al). MXenes as a biosensor can detect concentrations of metal ions and other biological molecules such as glucose and dopamine. A 3D porous MXene structure allows the diffusion of ions through channels that pass through. Much of the detection of either gases or biological molecular concentrations is due to the functional groups. By allowing either specific molecules to pass through or which molecule is blocked, biosensors and gas sensors are current research paths involving the application MXenes.

Methods of MXene Synthesis

The most common method of making MXenes is through wet chemical etching of atomic layers from the multi-layers of a MAX phase (Adibah et al.). This phenomenon is due to the weak layer-to-layer binding in the MAX phase rather than the intralayer one. MAX phases are soaked in acid to destroy bonds between transition metals and the A-element, typically hydrofluoric acid (HF). Experiments utilizing this method have noted that MXenes tended to have higher electronic conductivity compared to other methods and fewer atomic defects but could only use this for carbon-based MXenes as it fails to remove the A-layer from nitride-based MAX phases.

HF is very environmentally hazardous, thus necessitating the use of different etchants (U.S. Center for Disease Control). Improper disposal damages soil and water while posing serious health risks. Short-term exposure can lead to swelling of lung tissue, fluid buildup in the lungs, severe burns, and even death when in high quantities. Long-term vulnerability to HF leads to chronic lung disease. Fingertip injuries may result in persistent pain, bone loss, and deformation of the nail bed. Eye exposure to hydrogen fluoride may cause prolonged or permanent visual defects, blindness, or tissue destruction of the eye. A mixture of hydrochloric acid (HCl) and lithium fluoride (LiF) emerged in 2014, yet this process produces HF gases. Thus, various MXene synthesis methods must limit or eliminate HF use. This is highly critical for bio-related sensors, as trace amounts of HF can be lethal.

Urbankowski et al. first used the method of molten salt etching for MXene synthesis. The researchers combined Ti_4AlN_3 powder with a fluoride salt mixture with a 1:1 mass ratio, then heated the combination at 550 °C for 30 minutes. The resulting MXenes contained five different fluoride phases with Al, but the absence of Ti-containing fluorides indicated etching selectivity. Diluted sulfuric acid (H_2SO_4) and etching products dissolved Al-containing fluoride and are removed using deionized water, centrifugation, and decanting. XRD patterns show that this process removes all fluoride salts and leaves behind a powder of Ti4N3Tx and unetched Ti_4AlN_3. T represents OH or F surface termination in the former. To further purify the $Ti_4N_3T_x$ MXene, the product was combined with tetrabutylammonium hydroxide (TBAOH). The powder was further integrated with deionized water to be probed and centrifuged. The result underwent filtering one last time to collect small, unlayered flakes of $Ti_4N_3T_x$.

Given these methods, we chose a specific form of molten salt etching, the Lewis Acidic Salt Etching Method. This process eliminates using hydrofluoric acid (HF) in synthesizing MXenes. A mixture of copper (ii) chloride and various salts are ground with the MAX phase and heated to synthesize MXenes.

Importance of Cortisol

The hormone cortisol follows a circadian pattern, with elevated levels occurring during the mornings and low levels during the evenings (Cleveland Clinic). Currently, cortisol level testing requires blood tests; this process may be uncomfortable for patients and requires waiting several days for lab results, meaning that the results do not match current cortisol levels. Medical professionals must conduct the tests at specific periods for the disorder of interest. Thus, offering real-time data prevents misinformation concerning treatment for medical conditions and furthers personalized healthcare. This emerging field of medicine is shifting healthcare goals from reaction to prevention by factoring in lifestyle and user engagement.

Sweat sensing through wearable materials is a particular field of interest because it offers noninvasive and continuous monitoring throughout multitudes of physiological conditions; these factors allow for the early detection of disorders, while also allowing sports performance evaluations. Additionally, cortisol can gauge stress levels. A device offering "instantaneous" information could reveal the emotional states of young, even non-verbal, children to help communicate.

Results

To initially calibrate the resistance output by the Gamry EIS Potentiostat, a few baseline values (1 μg, 5 μg, 10 μg, and 15 μg) were tested on the sensor when a 12-mV current ran through. The resulting charge transfer resistance (R_{ct}) values (1978 Ω, 2434 Ω, 2567 Ω, 2948 Ω) were used to derive the calibration curve: y = 235x + 2417 with an R2 value of 0.977, as seen in Figure 2.

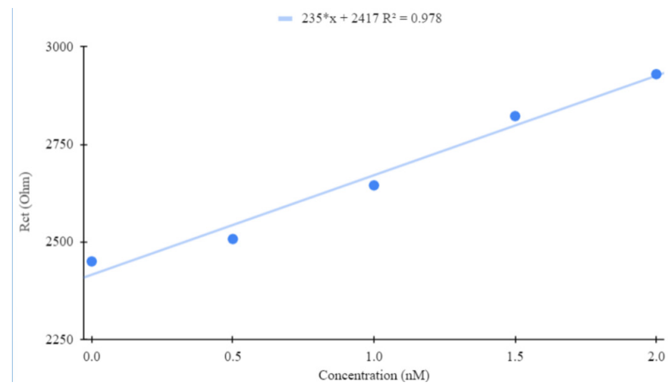

Figure 2. Calibration of Gamry EIS Potentiostat Resistance Output.

From this data, a continuous influx of cortisol was tested on the sensor, and the output is seen in Figures 3-5.

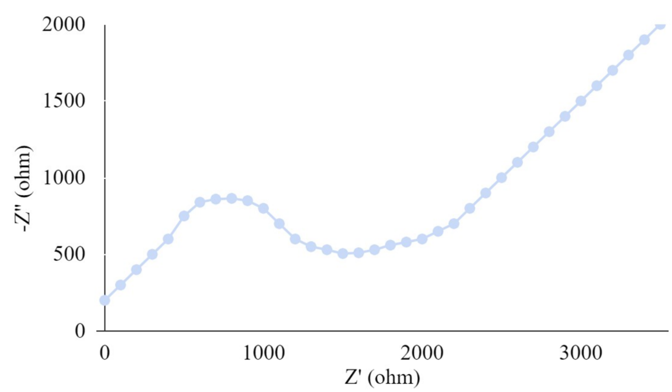

Figure 3. Nyquist Plot of the Cortisol Sensor.

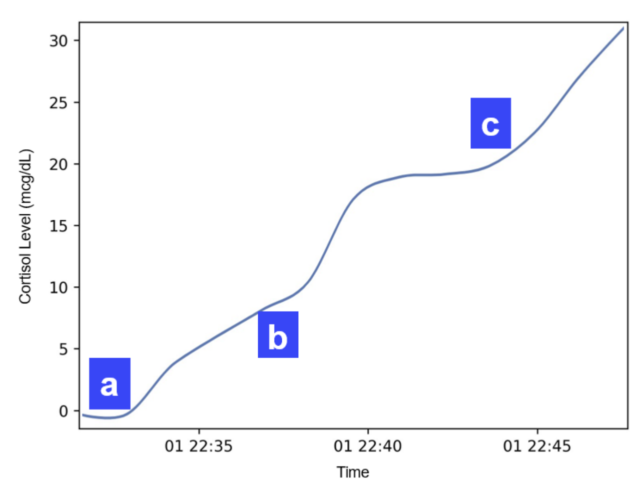

Figure 4. Cortisol Level as a Function of Time.

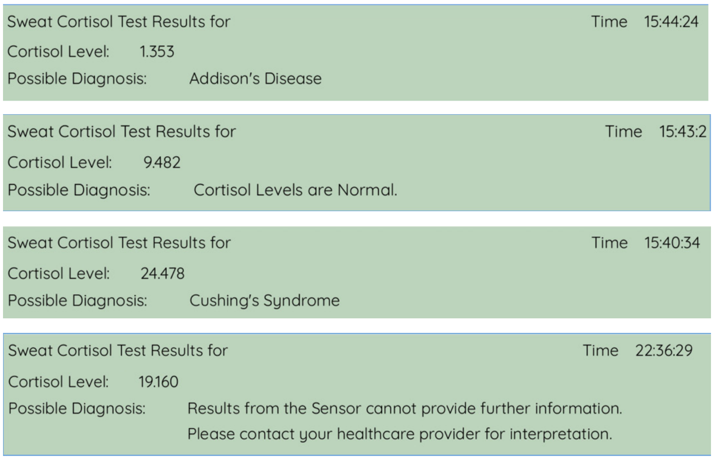

Figure 5. Summary of Continuous Cortisol Testing.

Finally, to test the accuracy of MCSS over continuous use, point-testing was performed to measure increments of error, as seen in Table 1.

Table 1. Point-Testing Results of MCSS over Continuous Use.

Sweat Sample	Spiked Cortisol Biomarker (μg)	Found Cortisol Biomarker (μg)	Sensor Recovery (%)
1	0.05	0.049 ± 0.005	98
2	5	4.81 ± 0.005	96.2
3	10	9.43 ± 0.005	94.3
4	25	23.45 ± 0.005	93.8

Note. The table shows the results of the point-test, where the sensor reads known cortisol values, and the calibration curve predicts the amount of the hormone. As the test progressed, the sensor accuracy fell from 98.0% to 93.5%.

Discussion

There are two major sources of error during this experiment. Primarily, a syringe injected the cortisol-spiked artificial sweat during testing. There is a possibility that a minute quantity of the fluid remained in the syringe and failed to reach the sensor during testing. Additionally, the reproducibility of the sensor decreased, as seen previously in Table 2, which is due to the MXene flakes being removed from the LBG through the movement of sweat.

Primarily, a Bovine Serum Albumin (BSA) treatment for samples should be utilized in future projects, as well as a binding treatment for the LBG and MXenes. This procedure will further prevent cortisol-like molecules from offsetting the measurement by binding to the antibodies and prevent the MXenes from flaking off. The antibodies should be unconjugated monoclonal rabbit-derived variations, as they are more specific than mouse variants. For future experimentation, the need for the physical Gamry potentiostat EIS can be eliminated through Bluetooth integration. This procedure is quite simple but needs the background of other professionals in the lab for successful implementation. Additionally, the console application can be further sophisticated for easy patient use. A newly developed program could include login information necessary for privacy, information regarding various disorders, as well as sending health data directly to a database a care provider can access. As the procedure becomes practiced, the retail cost of the sensor should also be minimized. Finally, MCSS can encapsulate a wide variety of hormones with increased sensor sensitivity. This component will allow a greater scope of healthcare management and can provide more insight to both the user and medical professionals.

Conclusion

The project had high accuracy detecting cortisol levels. Even after continuous experimentation, the sensor itself can be utilized multiple times with high sensor capabilities. This project will be continued at Western Michigan University over the coming summer to increase sensor stability and address the concerns provided during the Discussion. The resulting product can then be utilized commercially and entered the public market, not just used in research facilities.

If the project can become cheaper and more widely accessible, the sensor could be used in places ranging from homes, classrooms, psychiatric wards, and even elderly care facilities. This would allow ease in gauging stress levels and qualify patients to monitor their health. Personalized healthcare is a growing field enhanced by the SARS-CoV-2 pandemic, and the public is finding the experience convenient and timesaving. Furthering the future of medicine can allow patients to consult appropriate doctors sooner for better health outcomes. Further, medical professionals can treat patients better by having more insight into their personal lives. Presently, traditional doctor visits are noticeably short regarding physician-patient care, and this period will decrease as the US faces a drought of medical professionals and other healthcare workers. By advancing technology, the healthcare system gains efficiency and organizational capacity to reduce the burden of the ongoing healthcare crisis in the future.

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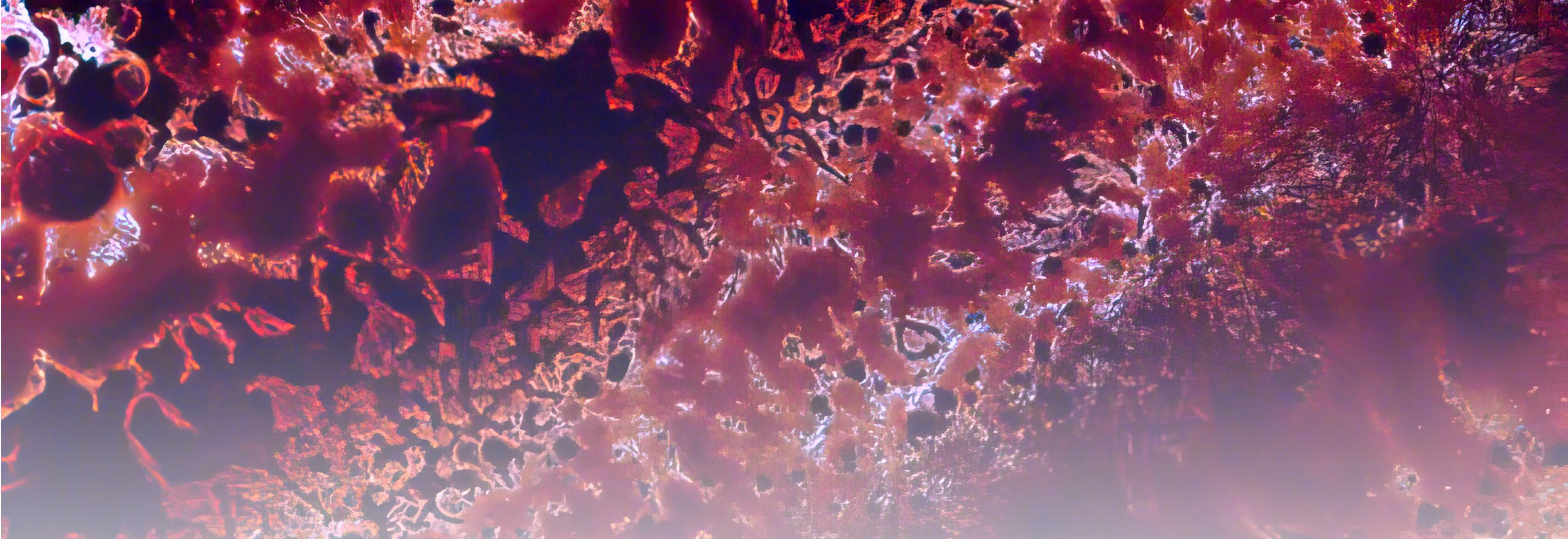

Degrees and Dollars: How Education Reduces Inequality

Olivia Lindsey[1,2], Alasdair Young[2]

My research journey began due to the desire to address and mitigate wealth disparity and the adverse effects it imposes on society. In addition to advancing understanding in the field of economic inequality, a professional goal of mine is to pursue higher education to further hone my skills and expertise. A potential future direction for my research involves exploring additional factors that could contribute to the reduction of wealth disparity.

Acknowledgements

I am grateful for all of the advice my professor Dr. Alasdair Young has provided throughout my research, in addition to his recommendation that I submit it to be published. I would like to also express my thanks to Dr. Whitney Buser for her counsel and support with the regression methodology, as well as all the guidance she has provided during my undergraduate years. Furthermore, I would like to thank Sharon Arulpragasm and Brice Dumas for their feedback during the writing process, Anthony Ahn and Carter Wilson for their assistance in the data preprocessing, and my editors Angelina Zhang and Alex Dubé for their help in getting this research published.

Abstract

Wealth disparity, a global and escalating societal challenge, has garnered increased attention as studies reveal the multifaceted implications of this phenomenon in the social, economic, and political dimensions. This paper investigates the role of higher education levels—upper secondary, tertiary, and below upper secondary—attained by citizens in Organization for Economic Cooperation and Development (OECD) countries in shaping wealth inequality. In order to do so, panel data from OECD databases spanning from 2010 to 2020 is utilized, generating regressions which incorporate the Gini index, education attainment proportions, and GDP per capita. Evidence across all countries suggests a higher education level reduces wealth disparity while a lower level increases inequality, supporting the Education and Equity theory. However, individual country analyses yield nuanced results. This could be due to a multitude of reasons, including but not limited to: multicollinearity, smaller sample sizes, compressed findings from the Gini index, and more.

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Introduction

Studies have demonstrated that higher levels of wealth disparity can lead to social division, stagnant economic growth, increased crime, and the erosion of the legitimacy of state institutions, as well as other factors (Wilkinson et al.; Heckman et al.; Choe). Therefore, previous literature has explored a spectrum of strategies in order to mitigate wealth inequality—such as government spending on wealthfare, widespread education attainment, progressive taxation, and market regulations (Huang and Ku; Piketty; Diamond and Saez). The focus of this research paper in particular will concentrate on the education solution, as the relationship between wealth disparity and education acquisition within nations in the Organization for Economic Cooperation and Development (OECD), or countries with free-market economies and democracies, is examined. The purpose of this investigation is to contribute to the ongoing debate on the relationship between education and wealth disparity, which can be categorized fundamentally into three schools of thought. The Education and Equity school of thought asserts that increased education leads to reduced wealth disparity; the Education and Stratification school of thought suggests that increased education may exacerbate wealth inequality; and the Systemic Factors and Disparity school of thought argues that broader structural factors play a more significant role than education alone. Overall, this paper intends to analyze data and trends over the period of ten years in order to contribute new insights and test the claims of each school of thought within the specific context of the OECD countries.

Specifically, this research will analyze whether the percentage and type of education—upper secondary, tertiary, and below upper secondary—attained by citizens in OECD countries play a role in economic inequality within these nations. According to the OECD, below upper secondary education encompasses preschool through roughly 6-8 years of primary classroom instruction. Upper secondary education includes instruction after primary school, for students typically between 15 to 18 years old. Tertiary education is categorized by the OECD as any and all schooling that builds upon upper secondary education, such as university, graduate school, or occupational training.

This investigation concentrates on the question: which level of education—upper secondary, tertiary, and below upper secondary—is most effective in reducing wealth disparity within OECD nations? The hypothesis is that higher education attainment will aid in diminishing wealth disparity and lower education attainment will increase wealth disparity, therefore reinforcing the Education and Equity school of thought. The intention of this study is to contribute to a deeper understanding of the influence of knowledge diffusion on wealth distribution in OECD countries. Empirically, analysis from this paper offers the opportunity to discover trends and patterns that demonstrate a relationship between varying education attainment and wealth disparity. In terms of policy relevance, this paper has the potential to provide policymakers with crucial insights on the factors that perpetuate wealth disparity and ultimately aid in formulating effective policies aimed at rectifying these imbalances and fostering equitable wealth distribution.

In order to study this research question, a quantitative analysis will be conducted utilizing data from the OECD databases. The data collected includes—the Gini index, which represents a measure of wealth disparity, the proportions of the population with education attainment levels for upper secondary, tertiary, and below upper secondary for each OECD nation, and gross domestic product (GDP) per capita for each country, all within in the period of 2010 to 2020. GDP per capita is being included as a control variable in order to take into account a nation's overall wealth, as that could potentially influence both the Gini index and education attainment, resulting in spurious association. OECD countries will be used in this research due to greater availability in data and increased consistency of data. The use of the Gini index provides a uniform measurement of economic inequality and the opportunity for meaningful cross-country comparisons, and has more data available compared to share of wealth, an alternative measurement. A cross-sectional panel regression analysis is then utilized to examine potential correlation between education-related factors and wealth disparity for all OECD countries throughout a span of several years, as well as regressions on each individual country in order to determine differing country effects.

The evidence from analyses conducted on all countries demonstrate that a higher level of education, upper secondary, attained by a country's population will ultimately reduce wealth disparity. In comparison, a lower level of education, below upper secondary, will increase wealth disparity. However, the case is not as clear-cut for tertiary education, which is statistically insignificant, and for individual country analyses, which will be expanded upon below. Ultimately the correlations and trends noted in the findings will aid policymakers due to the provision of evidence-based recommendations on policies that can address economic disparity.

The initial part of this research paper will delve into the existing body of literature in order to provide a comprehensive understanding of prior research on the education and inequality topic. This portion will proceed to demonstrate an analysis of a myriad of papers and books that present diverse perspectives on the influence of education attainment on wealth disparity. Next, the research methodology utilized will be introduced, as well as an elaboration on the data, variables, and central argument of this study. Afterwards, the findings derived from the aforementioned methodology will be presented and discussed regarding their significance, as well as connecting findings to the relevant schools of thought on the topic. Finally, the extent to which my findings answer the research question will be discussed, as well as challenges faced during the research and avenues for future studies.

Background

The Significance of Inequality

Wealth disparity is a pressing societal challenge and a phenomenon observed in every corner of the globe. Additionally, according to the Pew Research Center, the wealth gap has been widening in recent years—in 1980, U.S. households at the 90th percentile of earners had incomes about nine times the incomes of households at the 10th percentile, but in 2018 this ratio was about twelve and a half times, an increase of 39% (Horowitz et al.). Therefore, it is no surprise that in recent decades this subject has garnered increasing attention as studies evaluate the implications of the wealth gap in the economic, social, and political dimensions of industrialized and emerging countries alike. For example, in terms of social and public health elements of developed countries, one prevalent theory regarding the influence of inequality is that "most of the important health and social problems of the rich world are more common in more unequal societies" (Wilkinson et al. 173). Additionally, in Capital in the Twenty-First Century, author Thomas Piketty argues that inequality and the forces that push for increasing disparity are "potentially threatening to democratic societies and to the values of social justice on which they are based" (571). There have also been studies conducted which demonstrate links between inequality and lower social mobility (Heckman et al. 1), crime (Choe 33), and other factors. Overall, it can be noted that while the exact effects of wealth disparity on countries may differ from study to study, it is generally agreed upon that inequality is a multifaceted challenge that impacts societies on a myriad of levels. In conclusion, the findings from the aforementioned studies support the need to address this challenge in order to protect the health and welfare of modern societies.

Solutions to Disparity

The numerous studies on wealth disparity has led to a variety of theories and solutions being proposed, debated, and occasionally implemented over time to mitigate this challenge. One of the earliest theories on inequality was created by Simon Kuznets, who argued that there is a trend of increasing inequality in the early phases of industrialization, followed by a decline in inequality in the later phases of industrialization—also known as the Kuznets Curve (16-17). Today, wealth disparity research is centered primarily on the specific measures that can be undertaken in order to reduce the wealth gap, rather than presuming that increased development will naturally lead to reduced inequality. Some research studies assert that progressive taxation policies would be an effective way to ensure more equal wealth distribution (Diamond and Saez 166; Oishi, Kushlev, and Schimmack 157), while other policy makers focus on welfare spending and public service provision to reduce inequality (Huber, Nielsen, Pribble, and Stephens 960-961; Huang and Ku). Another prevalent theory is that higher levels of education attainment, or more investment in skills, can result in the reduction of wealth disparity (Mincer; Becker and Chiswick; Piketty). While the first two solutions to wealth disparity—taxation and welfare policies—concentrate primarily on reducing inequality of outcomes, higher education attainment instead aims to reduce inequality of opportunities. This research study will concentrate primarily on the third theory, observing the relationship between different levels of education attained and their influence on wealth disparity while factoring in the influence of the other alternative variables previously mentioned: progressive taxation and welfare policies. The next subsection will cover prevalent theories and the authors that support them regarding the relationship between education and wealth inequality within nations.

Arguments Around Education

In research between education and wealth disparity, there are primarily three schools of thought. The first school of thought, or Education and Equity school of thought, is centered around the Human Capital Theory, an early theory created by Gary Becker. This theory states that more investment in "human capital"—such as education and skills—will lead to increased productivity and higher income, potentially reducing wealth disparities (1). This idea has been referenced time and time again in more recent literature on education and wealth disparity; for example, Jong-Wha Lee and Hanol Lee stated in their research "Human Capital and Income Inequality" that "human capital, measured by educational attainment, plays an important role in income distribution" and "an increase in educational attainment reduces educational inequality and thus helps to reduce income inequality" (578). Therefore, the Education and Equity school of thought would expect there to be a positive and statistically-significant relationship between higher levels of education attainment and reduced wealth disparity.

In contrast, the second school of thought, or the Education and Stratification school of thought, maintains the opinion that education can actually be detrimental to wealth equality, with one of the earliest ideas being the Credentialist theory by Randall Collins. Collins' primary position is that employers use credentials to allocate more educated workers to better jobs, and that while more highly educated workers were finding more lucrative jobs, it ultimately was leading to further stratification of the workforce (9). An example of modern research that has concluded that education can increase wealth disparity is "Educational Opportunity and Income Inequality" by Igal Hendel, Joel Shapiro, and Paul Willen, which states that when attaining education becomes more affordable and available, "high-ability persons become educated and leave the uneducated pool, driving down the wage for unskilled workers and raising the skill premium" (841). The Education and Stratification school of thought would consequently presume there is a negative and statistically-significant relationship between higher levels of education attainment and reduced wealth disparity.

The third school of thought, the Systemic Factors and Disparity school of thought, argues that in the extensive discussion of contributors to inequality, education attainment is relatively unimportant, and policymakers must instead address the broader structural factors that result in inequality—such as access to resources, racism within societies, and regressive tax policies. One such study from this school of thought is by Richard Breen and Inkwan Chung, which concludes that "only about 20 percent of income inequality can be explained by a measure that distinguishes four categories of education" (470). Another study aligned with this theory argues that "improvements in education are not a sufficient condition to reduce income inequality" (Castelló-Climenta and Doménech 1). The Systemic Factors and Disparity school of thought would therefore anticipate that the relationship between higher levels of education attainment and wealth disparity to either not be statistically significant, or increased education attainment has less of an impact on inequality compared to other factors—such as access to resources, racism, and regressive tax policies. The research conducted in this paper will analyze trends and patterns in order to test the claims suggested by each school of thought. This comprehensive approach is intended to contribute to the increased understanding of the role that education plays in a country's inequality, as well as foster informed discussions for future research and decision-making. This paper diverges from existing literature as it will have a specific focus on the Organization for Economic Cooperation and Development (OECD) countries, as well as the inclusion of gross domestic product (GDP) per capita as a control variable, while adding important insights to the argument on the role of education in wealth disparity. Refer to Table 1 for a summary of the key theories regarding education and wealth disparity.

Table 1. Schools of Thought on Education and Wealth Equality

School of Thought	Key Claims	Authors Aligned
Education and Equity	More investment in education and skills will lead to increased productivity and higher income, reducing wealth disparities	Gary Becker, 1964; Jong-Wha Lee and Hanol Lee, 2018
Education and Stratification	Education can actually be detrimental to wealth equality, as more educated workers find better jobs this leads to further stratification of the workforce	Randall Collins, 1979; Igal Hendel et al., 2005
Systemic Factors and Disparity	In the discussion of contributors to inequality, education attainment is relatively unimportant and one must instead address the broader structural factors	Richard Breen and Inkwan Chung, 2015; Amparo Castelló-Climent and Rafael Doménech, 2014

Research Design

Research Question and Argument

The assessment of the literature has demonstrated several schools of thought regarding the relationship between education attainment and wealth disparity within countries: the Education and Equity school of thought, that more investment in education and skills will lead to a reduction in wealth disparities; the Education and Stratification school of thought, that education can actually be detrimental to wealth equality; and the Systemic Factors and Disparity school of thought, that education attainment is relatively unimportant, or not statistically significant, in reducing inequality. This research paper aims to illustrate the precise relationship between education and inequality within the context of the Organization for Economic Cooperation and Development (OECD) countries by analyzing the influence and significance of different levels, or amounts, of education attainment—upper secondary, tertiary, and below upper secondary—on the Gini index, a common measure of wealth disparity, throughout the span of 2010 to 2020 while additionally incorporating the control variable GDP per capita. Specifically, the question of this investigation is: which level of education attainment—tertiary education versus upper secondary versus below upper secondary—is most effective in reducing wealth inequality, as measured by the Gini index, within OECD countries? The hypothesis is that higher education attainment will aid in diminishing wealth disparity and lower education attainment will increase wealth disparity, with both demonstrating statistical significance. This would therefore reinforce the Education and Equity school of thought, rather than the Education and Stratification and Systemic Factors and Disparity schools of thought: more investment in education will lead to a reduction in wealth disparities. As a result, it implies that OECD countries with a larger percentage of the population attaining a higher level of education will demonstrate lower levels of wealth disparity compared to OECD countries with a larger percentage of the population attaining a lower level of education.

Data and Variables

The data for the variables utilized in this research stems from the Organization for Economic Co-operation and Development (OECD) databases, such as the "OECD Education Statistics" database, the "OECD Social and Welfare Statistics" database, and the "OECD National Accounts Statistics" database. The primary variables in this study are education attainment and wealth disparity, as well as gross domestic product (GDP) per capita as a control variable. The explanatory education attainment indicators measure the percent of the 25-64 year-old population that has achieved each level of education. These education attainment variables are categorized into three distinct levels of education: below upper secondary, upper secondary, and tertiary. These three levels of education have been developed and standardized by the OECD. Below upper secondary education covers preschool to approximately 6-8 years of primary classroom instruction (sixth to eighth grade in the U.S. system). Upper secondary education encompasses instruction for students aged between 15 to 18 (ninth to twelfth grade in the U.S. system). Tertiary education is schooling that builds on upper secondary education, and it can be academic education, but it also includes advanced vocational or professional education, such as university, graduate school, or occupational training (beyond twelfth grade in the U.S. system). This categorization allows for a comprehensive assessment of the impact of various amounts of education attainment on wealth inequality within countries. The data for these variables was found on the OECD website under the "OECD Education Statistics" database ("Adult education level (indicator)"). As the OECD database has already ensured consistency for analysis, no data manipulation is necessary for these variables.

For the response variable, the Gini coefficient was used to represent wealth disparity, as it is based on the comparison of cumulative proportions of the population against cumulative proportions of income received. The Gini index takes into account various sources of income, such as earnings, investments, and public cash transfers, and it additionally incorporates income taxes. Therefore, the Gini coefficient offers an extensive examination of the distribution of income and wealth, as well as integrating the impact of progressive taxation policies and welfare spending, two aforementioned alternative solutions, as potential factors in wealth distribution. This variable ranges between 0 in the case of perfect equality within a country and 1 in the case of perfect inequality within a country. The data for this variable was found from the OECD databases, particularly the "OECD Social and Welfare Statistics" dataset, and no additional data manipulation is necessary ("Income inequality (indicator)"). Utilizing the Gini index provides a standardized measurement of wealth inequality in each OECD country and the opportunity for meaningful cross-country comparisons, and while the Gini coefficient may compress findings more so compared to share of wealth, it does have more data available to analyze.

In order to ensure the validity of the research, an additional variable will be included: GDP per capita. GDP per capita, which measures a country's economic output per person, is a control variable included within the analysis in order to take into account a nation's overall wealth ("Gross domestic product (GDP) (indicator)"). Incorporating GDP per capita allows the potential influence of a nation's economic affluence on both education attainment and wealth disparity to be mitigated, ensuring the findings will accurately reflect the relationship between education attainment and wealth disparity. GDP per capita can impact inequality as it ultimately reflects a country's overall economic well-being. Higher GDP per capita may reduce inequality through policies that promote equitable income distribution, therefore, including it in the methodology is necessary.

In the literature review portion, there were two additional aforementioned solutions, or independent variables, that could potentially reduce wealth disparity besides education attainment: progressive taxation and welfare spending. While both are important in the discussion of inequality, they will not be included in the regression due to the fact that the Gini index already captures the effect of both alternative explanations, as it takes into account taxation and public cash transfers. Since the Gini coefficient incorporates social welfare expenditures and progressive taxation, then they must be removed from the regression in order to avoid multicollinearity, or high correlation between independent variables. Through a comprehensive analysis of these three variables, education attainment, GDP per capita, and wealth disparity, this paper will provide an extensive understanding of the complex socioeconomic dynamics within OECD nations and contribute valuable insights to the discussion on reducing inequality.

There are some limitations in the data however. First and foremost, two OECD countries, Japan and Chile, had to be excluded due to their insufficient amount of data on education attainment levels. While their omission from the analysis is necessary to ensure reliability, it does mean that there will be some potential limitations in the findings. In particular, this omission implies that the ability of the findings to inform policy-making decisions in these excluded nations may be restricted. Additionally, not every OECD country in the dataset has the Gini coefficient for every year from 2010-2020. In fact, most countries may be missing this data for one or two years. This makes it more difficult to analyze the trends in wealth disparity accurately, and may limit cross-country comparisons. Only OECD countries with at least five years of data on their Gini indexes, or at least half of the time period of 2010 to 2020, were included for analysis, meaning that Belgium and Columbia were removed as well. For the countries with a few missing data points, Excel was utilized for data approximation, which ultimately creates a degree of uncertainty in the results. The data for the Gini index, below upper secondary, upper secondary, and tertiary education can be seen in Table 14, Table 15, Table 16, and Table 17 respectively in the Appendix. The data points which were approximated are highlighted in yellow.

Methodology

For the methodology, this research will utilize multivariable linear regressions to best analyze the aforementioned variables. Four time series regressions for each OECD country will be constructed, as well as four cross-sectional panel regressions that encampasses all countries. These regressions will incorporate the Gini coefficient, GDP per capita, and education attainment levels. As previously mentioned, this research will not include the alternative solutions to wealth disparity—progressive taxation and welfare spending—as variables to analyze due to the fact that the Gini index already integrates the impact of taxation and public cash transfers. Equations 1 to 4 demonstrate the models of the education attainment regressions, which will be utilized for each individual country as well as all countries combined:

$$gini_c = B_0 + B_1 * us_c + B_3 * tert_c + B_4 * gdp_c \quad (1)$$

$$gini_c = B_0 + B_1 * bus_c + B_2 * gdp_c \quad (2)$$

$$gini_c = B_0 + B_1 * us_c + B_2 * gdp_c \quad (3)$$

$$gini_c = B_0 + B_1 * tert_c + B_2 * gdp_c \quad (4)$$

Equations 1-4. $gini_c$ represents the Gini coefficient of each country (c) over the time period 2010 to 2020. bus_c represents the percentage of the population of each country with below upper secondary education in the time period. usc is the percentage of the population of each country with upper secondary education in the time period. $tert_c$ is the percentage of the population of each country with tertiary education in the time period. gdp_c is the GDP per capita for each country in the time period. Equation 1 only includes upper secondary and tertiary education, as including all three education levels is not possible due to multicollinearity.

For the first equation, only upper secondary and tertiary education were included as including all three education levels in the same regression model introduces perfect multicollinearity, which leads to unreliable results. Therefore, this research will primarily explore the upper levels of education for more robust findings. Moreover, conducting regressions for individual countries and an overall analysis that encompasses all countries offers several benefits. First and foremost, individual country regressions provide vital insights into the unique relationships between the variables within each nation, therefore displaying country-specific factors and results that may not be apparent in a global context. While each individual country will have less data points than the overall analysis, this comparative approach allows for a deeper understanding of precisely how inequality within different OECD nations is influenced by education attainment and can provide important policy implications for each nation. Furthermore, an overall analysis allows me to identify trends on a global level, and the increased sample size leads to more generalizable findings and offers a comprehensive understanding of the role of education within OECD nations.

Afterwards, to test the hypothesis that countries with higher proportions of the population attaining higher levels of education generally have lower Gini coefficients, t-tests will be conducted on the coefficients, or betas, of all three education attainment variables in the regressions to demonstrate their statistical significance. Assuming that the betas for the higher levels of education, such as tertiary versus below upper secondary and upper secondary, or upper secondary versus below upper secondary, are negative as well as statistically significant (non-zero with a p-value of 0.05 or lower) and the beta for the lower levels of education, such as below upper secondary versus upper secondary and tertiary, or upper secondary versus tertiary, is positive and statistically significant, it will be possible to empirically prove that countries with a larger proportion of the population attaining higher levels of education have less inequality, thus disproving the Education and Stratification and Systemic Factors and Disparity schools of thought. In conclusion, these regressions and t-tests will allow for the ability to capture the complex dynamic relationships between wealth disparity and differing levels of education attainment, and the findings will relate to the aforementioned schools of thought.

Findings

Overall, a total of 140 regressions have been conducted in order to analyze the precise relationship between varying levels of education attainment and wealth disparity on both the country level and OECD countries in general—four regressions for each of the thirty-four countries, as well as four regressions for all OECD nations overall. Tables have been generated which summarize these findings. Below includes the tables and findings from these analyses.

Cross-Sectional Panel Analysis

As stated above, four cross-sectional panel regressions for the overall OECD nations have been conducted. Table 2 represents the results of these regression models.

Table 2. All Nations Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
bus		0.00189*** (0.000148)		
us	-0.00255*** (0.000150)		-0.00255*** (0.000149)	
tert	7.97e-05 (0.000247)			0.000432 (0.000328)
gdp	-1.18e-06*** (1.39e-07)	-5.30e-07*** (1.35e-07)	-1.15e-06*** (1.15e-07)	-1.22e-06*** (1.86e-07)
Constant	0.474*** (0.0102)	0.297*** (0.00781)	0.476*** (0.00840)	0.355*** (0.00977)
Observations	374	374	374	374
R-squared	0.507	0.388	0.507	0.121

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

For the explanatory variable below upper secondary education (bus), Model 2 demonstrates that it is positively linked to wealth inequality, as well as being very statistically significant—meaning a higher proportion of the population having below upper secondary education is indicative of higher wealth inequality. Models 1 and 3 both demonstrate that upper secondary education has a negative relationship with Gini Index, with both coefficients having strong statistical significance. Finally, Models 1 and 4 display a positive relationship between tertiary education and wealth inequality, however, neither model demonstrates a statistically significant relationship between the two. This suggests that the association between tertiary education and wealth inequality is not strong. These findings are partially more consistent with the Education and Equity school of thought than the Education and Stratification and Systemic Factors and Disparity schools of thought due to the fact that less education, below upper secondary, is positively associated with wealth disparity while more education, upper secondary, is negatively associated. However, in the case of tertiary education, the Systemic Factors and Disparity school of thought best aligns with the findings for that explanatory variable as the regressions demonstrate no significant relationship between it and the Gini coefficient.Additionally, in terms of the control variable, GDP per capita, it can be noted that across all models higher GDP per capita (represented by gdp) is consistently associated with lower wealth inequality, with all models having statistical significance of a p-value below 0.001. Overall, these findings highlight the complex relationships between varying education levels, economic output, and wealth inequality across a dataset of 374 observations. To further explore these complex relationships, individual country analyzes are planned in order to identify individual trends.

Individual Time-Series Analyses Introduction

In the individual regressions for below upper secondary, upper secondary, and tertiary education levels, the majority of the 34 countries in the dataset did not exhibit statistical significance. The countries with no statistical significance are: Australia, Austria, Czech Republic, Denmark, Estonia, France, Germany, Hungary, Ireland, Israel, Italy, Latvia, Lithuania, Netherlands, New Zealand, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, and United Kingdom. This lack of statistical significance suggests that, for these countries, the relationship between education levels and wealth inequality does not follow the clear and consistent pattern noted in the overall regression. There are a few reasons for this phenomenon. First and foremost, the individual country regressions have smaller sample sizes, meaning the statistical power to detect significant relationships diminishes. Additionally, the use of the Gini index as a measure of inequality means an individual country's year to year fluctuations are condensed, therefore compressing findings, which may further contribute to the observed lack of statistical significance in individual regressions. The results could additionally suggest that on the individual level, the majority of countries conform to the Systemic Factors and Disparity school of thought and policymakers should focus on factors beyond education attainment to reduce inequality. In the upcoming sections, the tables of the countries that do demonstrate one or more statistically significant relationships between the explanatory and response variables have been included in order to define the individual country association with the other two schools of thought—Education and Equity and Education and Stratification.

Education and Equity Countries

The following countries had findings that aligned with the Equation and Equity school of thought: Canada, Finland, Greece, Korea, Mexico, and the United States. These countries compose 17.64% of the countries in the dataset.

For Canada (Table 3), below upper secondary and upper secondary education both have positive statistically significant relationships with the Gini index, but tertiary education has a negative statistically significant relationship with it. This supports the Education and Equity school of thought, and implies that Canadian policymakers should emphasize a greater proportion of the population getting tertiary education to reduce inequality.

Similar to Canada, Finland (Table 4) supports the Education and Equity school of thought, as tertiary education has a significant negative relationship with the Gini index in both Models 1 and 4 and below upper secondary education has a significant positive relationship with the Gini index. This means policymakers should emphasize increasing tertiary or decreasing below upper secondary education in its population to reduce inequality.

Table 3. Canada Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	-0.0111 (0.0128)		0.00813* (0.00250)	
tert	-0.0123 (0.00807)			-0.00546** (0.00144)
gdp	3.49e-06 (1.56e-06)	3.55e-06* (1.47e-06)	2.32e-06 (1.47e-06)	3.03e-06 (1.45e-06)
bus		0.0142** (0.00348)		
Constant	1.220 (0.864)	0.0100 (0.0987)	-0.0836 (0.151)	0.471*** (0.0337)
Observations	11	11	11	11
R-squared	0.779	0.778	0.706	0.756

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table 4. Finland Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	-0.000283 (0.00184)		0.00214 (0.00323)	
tert	-0.00341** (0.000764)			-0.00337** (0.000684)
gdp	2.75e-06*** (4.71e-07)	2.35e-06*** (4.64e-07)	8.84e-07 (4.02e-07)	2.75e-06*** (4.40e-07)
bus		0.00324** (0.000847)		
Constant	0.298* (0.0941)	0.116** (0.0314)	0.129 (0.158)	0.284*** (0.0117)
Observations	11	11	11	11
R-squared	0.869	0.812	0.496	0.869

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

While Models 2-4 do not demonstrate any statistical significance for the explanatory variables for Greece (Table 5), Model 1 supports the Education and Equity school of thought, as less education, in this case upper secondary, increases inequality and more education, tertiary education, reduces it. Greek policymakers should therefore focus on increasing tertiary education in their country.

Table 5. Greece Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.0122* (0.00414)		-0.00113 (0.00168)	
tert	-0.00989* (0.00297)			-0.00150 (0.00112)
gdp	-2.70e-06 (1.27e-06)	-4.61e-06* (1.62e-06)	-5.11e-06* (1.57e-06)	-4.23e-06* (1.62e-06)
bus		0.000718 (0.000683)		
Constant	0.197 (0.102)	0.434*** (0.0606)	0.516*** (0.0535)	0.489*** (0.0315)
Observations	11	11	11	11
R-squared	0.898	0.756	0.738	0.774

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Korea's (Table 6) findings back the Education and Equity school of thought, as tertiary education is significantly negatively associated and below upper secondary is significantly positively associated. Korean policymakers should therefore focus on reducing the proportion of the population with below upper secondary education or increasing the proportion with tertiary education.

Table 6. Korea Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	-0.00569		0.00332	
	(0.00590)		(0.00680)	
tert	-0.00731*			-0.00596*
	(0.00258)			(0.00216)
gdp	6.88e-07	4.32e-07	-3.49e-06*	7.44e-07
	(1.82e-06)	(1.52e-06)	(1.46e-06)	(1.81e-06)
bus		0.00742*		
		(0.00241)		
Constant	0.895*	0.237*	0.360	0.603***
	(0.304)	(0.0925)	(0.326)	(0.0324)
Observations	11	11	11	11
R-squared	0.965	0.965	0.925	0.961

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

For Mexico (Table 7), these regressions demonstrate conformity with the Education and Equity theory. The two higher levels of education have significant negative relationships with the Gini index in Models 3 and 4, and below upper secondary has a significant positive relationship with it. Therefore, policymakers should focus on initiatives that promote higher education, such as upper secondary or tertiary.

Table 7. Mexico Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	-0.00167		-0.0122**	
	(0.00985)		(0.00264)	
tert	-0.0104			-0.0120***
	(0.00943)			(0.00233)
gdp	-1.37e-06	-9.48e-07	-5.65e-07	-1.57e-06
	(2.42e-06)	(2.10e-06)	(2.34e-06)	(1.98e-06)
bus		0.00614***		
		(0.00121)		
Constant	0.682***	0.0757	0.699***	0.679***
	(0.0342)	(0.110)	(0.0309)	(0.0264)
Observations	11	11	11	11
R-squared	0.907	0.905	0.891	0.907

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Finally, the United States' (Table 8) findings agree with the Education and Equity theory. Tertiary education is negatively related with inequality, while the lower level of education, upper secondary, is positively associated—both with significance. Therefore, US policymakers should emphasize a higher proportion of the population achieving tertiary education to reduce inequality.

Table 8. United States Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.00443		0.00951**	
	(0.00761)		(0.00281)	
tert	-0.00325			-0.00568**
	(0.00451)			(0.00164)
gdp	2.11e-06	5.65e-07	2.21e-06*	1.84e-06*
	(9.38e-07)	(6.23e-07)	(8.99e-07)	(7.74e-07)
bus		0.00919		
		(0.00402)		
Constant	0.222	0.269**	-0.158	0.546***
	(0.557)	(0.0740)	(0.176)	(0.0337)
Observations	11	11	11	11
R-squared	0.789	0.667	0.773	0.779

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Overall, these six countries demonstrate that a larger proportion of their populations acquiring a higher level of education is beneficial for reducing inequality, while their populations obtaining a lower level of education can increase inequality. A higher level can be tertiary versus upper secondary / below upper secondary, or just upper secondary versus below upper secondary.

Education and Stratification Countries

The following countries had findings that aligned with the Equation and Stratification school of thought: Costa Rica, Iceland, and Norway. These countries compose 8.82% of the countries in the dataset.

Costa Rica (Table 9) aligns better with the Education and Stratification theory, as higher and middle education, tertiary and upper secondary, are positively correlated with the Gini index and below upper secondary is negatively correlated with it, with all having statistical significance. Since Costa Rica only recently joined the OECD and has yet to fully integrate its policies, it will be interesting to note how this relationship develops over time.

Table 9. Costa Rica Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.00626		0.0105*	
	(0.00581)		(0.00441)	
tert	0.00321			0.00530*
	(0.00293)			(0.00222)
gdp	-1.37e-06	-1.31e-06	-1.13e-06	-1.01e-06
	(8.84e-07)	(8.21e-07)	(8.67e-07)	(8.27e-07)
bus		-0.00416*		
		(0.00150)		
Constant	0.329**	0.757***	0.329***	0.378***
	(0.0619)	(0.102)	(0.0627)	(0.0421)
Observations	11	11	11	11
R-squared	0.517	0.508	0.434	0.436

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

For Iceland (Table 10), upper secondary and tertiary education have no significant relationship with the Gini index, while below upper secondary has a significant negative relationship. This therefore implies that a higher proportion of the population having below upper secondary reduces inequality, reinforcing the Education and Stratification theory, which states higher education can be detrimental to equality.

Table 10. Iceland Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.00413		0.00258	
	(0.00180)		(0.00169)	
tert	0.00412			0.00109
	(0.00252)			(0.00266)
gdp	-1.09e-06	-1.09e-06	7.29e-07*	3.86e-08
	(1.14e-06)	(6.82e-07)	(2.68e-07)	(1.27e-06)
bus		-0.00412*		
		(0.00164)		
Constant	0.00564	0.418***	0.123	0.211***
	(0.0949)	(0.0771)	(0.0680)	(0.0387)
Observations	11	11	11	11
R-squared	0.628	0.629	0.485	0.348

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Similar to Costa Rica, the findings from Norway (Table 11) align better with the Education and Stratification theory, as higher education, tertiary schooling, is positively correlated with the Gini index and the middle and lower education, below upper secondary and upper secondary schooling, are negatively correlated with the Gini index, with all having statistical significance. Below upper secondary education appears to have the strongest negative influence on the Gini index.

Table 11. Norway Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.00407		-0.00254**	
	(0.00359)		(0.000607)	
tert	0.00602			0.00240**
	(0.00323)			(0.000487)
gdp	-7.36e-07	-8.18e-07	-3.47e-07	-5.18e-07
	(3.76e-07)	(5.53e-07)	(3.58e-07)	(3.29e-07)
bus		-0.0113*		
		(0.00412)		
Constant	-0.109	0.513***	0.384***	0.192***
	(0.267)	(0.0997)	(0.0385)	(0.0231)
Observations	11	11	11	11
R-squared	0.791	0.485	0.688	0.753

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Overall, these three countries demonstrate that a larger proportion of their populations acquiring a higher level of education is detrimental for reducing inequality, while their populations obtaining a lower level of education can increase equality.

Additional Findings

Luxembourg (Table 12) is unique, as both tertiary and below upper secondary education have no statistical significance, but upper education is positively linked with the Gini index. This implies as long as the proportion with upper education decreases, whether by obtaining more or less education, inequality will decrease. This phenomenon does not align with either the Education and Equity or Education and Stratification theories. These findings could therefore relate to the Systemic Factors and Disparity school of thought.

Table 12. Luxembourg Regressions

VARIABLES	(1) gini	(2) gini	(3) gini	(4) gini
us	0.00162		0.00162*	
	(0.00120)		(0.000675)	
tert	5.80e-06			-0.00143
	(0.00133)			(0.000844)
gdp	6.05e-08	-6.39e-07	6.07e-08	-1.80e-07
	(4.45e-07)	(3.16e-07)	(4.12e-07)	(4.28e-07)
bus		-0.00122		
		(0.00138)		
Constant	0.252	0.411***	0.252**	0.395***
	(0.109)	(0.0344)	(0.0652)	(0.0274)
Observations	11	11	11	11
R-squared	0.681	0.502	0.681	0.597

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Individual Time-Series Analyses Summations

Overall, on the individual level, six countries—Canada, Finland, Greece, Korea, Mexico, and the United States—exhibit findings that correlate with the Education and Equity school of thought while three countries—Costa Rica, Iceland, and Norway—reinforce the Education and Stratification school of thought (due to the complex nature of Luxembourg's findings, it does not exactly support any theory, which in itself could fall under the Systemic Factors and Disparity school of thought). This implies that politicians for the first six countries should emphasize policies that promote higher education attainment for its population, while politicians for the latter three should focus on reevaluating educational policies that lead to further stratification. The rest of the countries in the dataset did not have any statistical significance for any of the variables, implying that on the individual level the Systemic Factors and Disparity argument is more prevalent and education may not be a sufficient solution to wealth disparity. Granted, for the overall regressions there was strong support for the Education and Equity theory, as a higher level of education, upper secondary education, reduced inequality while its lower level counterpart, below upper secondary education, increased inequality—although the highest level of education, tertiary education, did not play a role in shaping a nation's inequality. The results imply that for OECD nations as a whole, a larger proportion of the population attaining higher education beyond below upper secondary education is beneficial in reducing wealth inequality. As previously stated, the reason why this trend was not as apparent on the individual country level may be due to multicollinearity, smaller sample sizes, compressed findings from the Gini index, outliers, and a plethora of other challenges that would need to be examined more thoroughly in future research. Refer to Table 13 which summarizes the findings and their relationship to the key theories regarding education and wealth disparity.

Table 13. Findings and Their Relation to the Schools of Thought

Education & Equity	Education & Stratification	Systemic Factors & Disparity
6 countries; 17.64%	3 countries; 8.82%	25 countries; 73.53%
Canada, Finland, Greece, Korea, Mexico, and the United States	Costa Rica, Iceland, and Norway	Australia, Austria, Czech Republic, Denmark, Estonia, France, Germany, Hungary, Ireland, Israel, Italy, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, and United Kingdom

Conclusion

In conclusion, this paper has delved into the complex relationships between varying levels of education attainment and wealth disparity in OECD countries, while incorporating GDP per capita as a control variable. The findings for the overall regressions strongly demonstrate the presence of a positive relationship between higher education, upper secondary versus below upper secondary, and reduced inequality for the OECD nations as a whole. However, tertiary education did not demonstrate significant influence on inequality and the individual country regressions reveal more nuanced patterns, with some nations aligning with the Education and Equity school of thought, which emphasizes the positive impact of higher education attainment on reducing wealth disparity, while others align with the Education and Stratification theory, suggesting that educational policies in these regions may inadvertently contribute to further social stratification. These insights highlight the need for tailored policy approaches, as policymakers must consider the unique challenges and characteristics of their individual nations. In the future, research could possibly delve deeper into the specific contextual factors influencing the observed trends, explore alternative measures of wealth disparity beyond the Gini Index, or examine countries outside of the OECD.

Please scan here to see Works Cited & the Appendix.


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