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Advancing environmental justice research within and beyond science and engineering

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Abstract

Scientists and engineers have historically approached questions of environmental justice (EJ) differently from social scientists and humanists, from how they formulate problem scope to how they propose solutions. While scientists and engineers have assessed distributional injustices extensively, there are opportunities for deeper interdisciplinary collaboration with other EJ schools of thought. In this perspective, we first present an EJ schematic for a science and engineering audience, where we trace epistemologies within EJ schools to show how EJ scholars conceptualize knowledge, how this relates to their methods, and how they present and publish work. We survey the EJ literature – mainly work related to the United States – across disciplines to determine major tensions within EJ and between EJ, science, and engineering scholarship. We also discuss possibilities for enabling interdisciplinary collaboration for scientists and engineers working on EJ-related questions by analyzing epistemological compatibilities. Next, we highlight opportunities to facilitate collaboration through an illustrative interdisciplinary case study. We conclude with takeaways for scientists and engineers moving forward, alongside some of the challenges accompanying interdisciplinary EJ research.

Synopsis

This perspective traces different approaches to environmental justice scholarship to indicate opportunities for cross-disciplinary collaborations with science and engineering research.

Keywords

Environmental justice, interdisciplinary, collaboration, environmental equity, United States

1. Introduction

Environmental justice (EJ) scholarship has traditionally been dominated by law, public policy, public health, and the social sciences. Over the last few decades, scholars based in applied sciences including and extending beyond public health, all referenced here as science and engineering (S&E), have been motivated by the social and ethical implications of their research. This broadening has brought new opportunities and challenges to the EJ field beyond its origins in case studies, cross-sectional analyses, and historical analyses. Numerous articles have captured these changes with synthetic overviews and analyses of EJ research.[1–12]

EJ scholars differ in how they frame and study problems. They use distinct terminologies to describe problem origin, apply discipline-specific methods, and communicate findings within their own research communities and with other actors. These variations – rooted in differing philosophical paradigms and disciplinary assumptions – create disciplinary differences of approaches to EJ research.[13–16] How activists and advocates attribute blame for injustices and call for redress can also differ from how researchers describe problems or solutions.[17] Interdisciplinary collaboration can help to overcome the differences in discourses by drawing on multiple perspectives in problem scoping, clarifying the role academic research can play in the solution space, and identifying shortcomings of proposed solutions.[18,19] The convergence of historical injustices and current and future climate crises – entanglements of vulnerabilities, impacts, and tipping points – is an example of complex problems that need interdisciplinary approaches to advance equity and sustainability.[16,19–25]

Scholars have distinguished the terms interdisciplinary, multidisciplinary, and transdisciplinary, particularly around the level of collaboration. Some researchers acknowledge but do not try to solve differences in epistemological approaches, while others try to understand the problem and develop methods that intertwine knowledge from multiple fields.[16,26,27] For this perspective, we define interdisciplinary collaboration as any work that calls on two or more established academic disciplines and include any level of cross-disciplinary collaboration.[28] Working only within disciplinary boundaries, researchers may overlook the limitations of their tools or unknowingly perpetuate harmful biases.[16] S&E researchers are often trained to consider objectivity and parsimony as core aspirations, but they may also find themselves collaborating with social scientists or advocates who more transparently acknowledge how their experiences and positionality shape their work.

There are numerous case studies that showcase the value of interdisciplinary S&E work. For example, Nsude et al. create a framework that considers historical environmental injustices to avoid perpetuating injustices in the deployment of future renewable energy resources. They develop methods to uncover evidence of injustices and exclusion of communities using a critical restoration geography lens.[29] This type of work can influence the siting of renewable energy projects, prioritizing community concerns in the planning and design of the built environment. Such interdisciplinary approaches enable researchers to pursue novel lines of inquiry and ask questions that cannot be answered within disciplinary silos, making research more transformational in terms of its rigor, relevance, reach, and policy impact.[30]

Scientists and engineers working on EJ have primarily focused on assessing the existence and distribution of injustices. Examples include research investigating whether toxins disproportionately impact marginalized groups and studies that analyze historical and future policy impacts on existing inequities.[31–35] Scholars, such as Gwen Ottinger, have provided recommendations on how to conduct EJ research within science and technology studies (STS) and engineering disciplines.[36–42] Prioritizing community needs and knowledge in S&E research has been extensively analyzed, alongside rethinking collaboration between academic and non-academic entities on EJ-related initiatives.[43,44] We build on this body of literature to systematically characterize the range of discourses and epistemologies within EJ-related research to indicate how and where S&E researchers could effectively build bridges across disciplinary divides.

In this piece, we characterize the main lines of work within EJ to propose a schematic for interdisciplinary research to advance S&E and EJ. We explore where major scholarly tensions exist within diverse epistemological views to EJ-related topics and between S&E research approaches and EJ research. We discuss how to overcome some of these tensions to facilitate collaboration between S&E researchers and non-S&E researchers and to identify where the major challenges to justice-facing collaboration lie. Our primary audience is S&E scholars who are interested in 1) addressing environmental injustices through their work, and 2) reflecting on how their training has shaped how they process problems and brainstorm solutions. S&E researchers who are interested in conducting EJ research need to understand diverse worldviews and EJ concepts to explore avenues for collaboration, expand questions asked, and rethink what constitutes relevant research products.

This perspective is structured as follows: first, we provide key definitions and significant disciplinary and ethical tensions in the EJ literature. We then develop the outlines of an EJ research schematic, tracing how philosophical views shape the research process and products to position research and researchers within the existing range of discourses. Third, we apply concepts from the EJ research schematic to analyze one EJ-centered S&E study. We conclude with lessons for scientists and engineers who approach their work through the lens of EJ.

2. Definitions

The EJ movement in the U.S. was founded in activism that combined demands for social justice and a safe environment for all, spawning new avenues of research inquiry across environmental health, the social sciences, and (less frequently) S&E fields.[45] EJ has been variously defined in the literature, but the core of these definitions always includes what the Environmental Protection Agency references as "fair treatment and meaningful involvement of all people" in environmental policy and regulation.[46] There are three long standing categories of EJ in the literature:

- **Distributive:** Focuses on the unequal allocation of environmental hazards/benefits and was the initial goal of the EJ movement, such as proving that disparate impacts exist by race and class.[8,47]
- **Procedural:** Emphasizes the rights of affected communities to participate in decision-making processes.[8,47]
- **Recognitional**: Calls for recognizing, valuing, and respecting diverse identities, histories, and perspectives of marginalized peoples.[8]

The latter two categories can be thought of as reasons why distributive injustices occur and persist. In particular, recognitional justice may be a prerequisite for sustained distributional justice.[8] Additional categories of justice and injustice are also being defined and debated, such as restorative justice based on rectifying historical injustices and extractive practices with nature,[9] and corrective justice calling for polluters to be made responsible for redress.[5,47,48] We highlight two tensions within the literature that distinguish the philosophical views and perspectives that we summarize below.

The Role of the State and the History of Injustice: The first tension in EJ literature is problem contextualization. When an injustice is identified, researchers often take one of two stances: 1) historicizing the problem and determining how legacies of the past have created and perpetuate existing injustices, or 2) proposing a solution to the urgent distributional problem with (usually) little historical context.[5,7,9,50] Some scholars in the first stance argue that the origin of injustices is colonialism and capitalism (specifically racial capitalism in some contexts).[7,9,51–53] They assert that injustices were created by 'the state,' or agencies associated with the state, such as governing bodies; regulators; private organizations; nonprofits; and international organizations. Historicizing injustices has led some scholars to eschew turning to the state for redress because they view the state as complicit, while other scholars – acknowledging the role the state has played – have argued in favor of working with and remedying concerns within the state apparatus.[7,9,52,54,55] In the second stance, scholars may assign blame to the state for

environmental injustices, but they continue to rely on the state – especially courts, as well as regulation – to remediate mainly distributional problems and to rectify injustices. These two approaches have led EJ scholars to be "deliberative democrats" (work within the system) or "activists" (work by pressuring the system from the outside) with different positions on how injustice manifests and whom we can turn to for redress.[49] Many scholar-activists engage in both forms of pressure and advocacy, depending on the nature of the injustice and the nature of the governance regime.

Value of Lives: The second tension relates to how life is valued and prioritized. Some scholars focus on alleviating injustices for populations who have been marginalized based upon definitions of race, class, gender, etc. Multiple axes of marginalization build upon one another and are intersectional in practice.[7,56] Meanwhile, other scholars have argued that non-human entities should also be prioritized, attributing life and value to animals, Earth, and water.[7,57–59] The equal valuation of non-human life means that the exploitation of natural resources is itself an injustice to communities.

Positions on the role of history, the state, humans and non-humans, and intersectionality determine how solutions are put forth to address injustices across categories of justice. For instance, some scholars argue that equitable distribution of harmful products for humans ignores the rights of non-humans since inequitable harms to these entities still occur with the exploitation of natural resources. Recognizing harms beyond the anthropocentric extends traditional EJ frameworks that were dominant prior to the formal introduction of critical EJ in 2017.[7,60] The three main categories of EJ have also been critiqued as reflecting "Western" ways of thinking that may not apply to environmental or justice struggles in the Global South.[57,60]

3. An Environmental Justice Research Schematic

We present a three-layer schematic to explain how different fields – engineering, law, public policy, public health, anthropology, sociology, etc. – approach similar problems and highlight the most generative and constructive areas for cross-disciplinary collaborations: 1) broad philosophical views (values and assumptions that underlie research approaches), 2) EJ-specific perspectives (derived from philosophical views), and 3) research processes (research design, methods, and presentation of results) associated with specific EJ perspectives. The boundaries of these layers sometimes overlap.

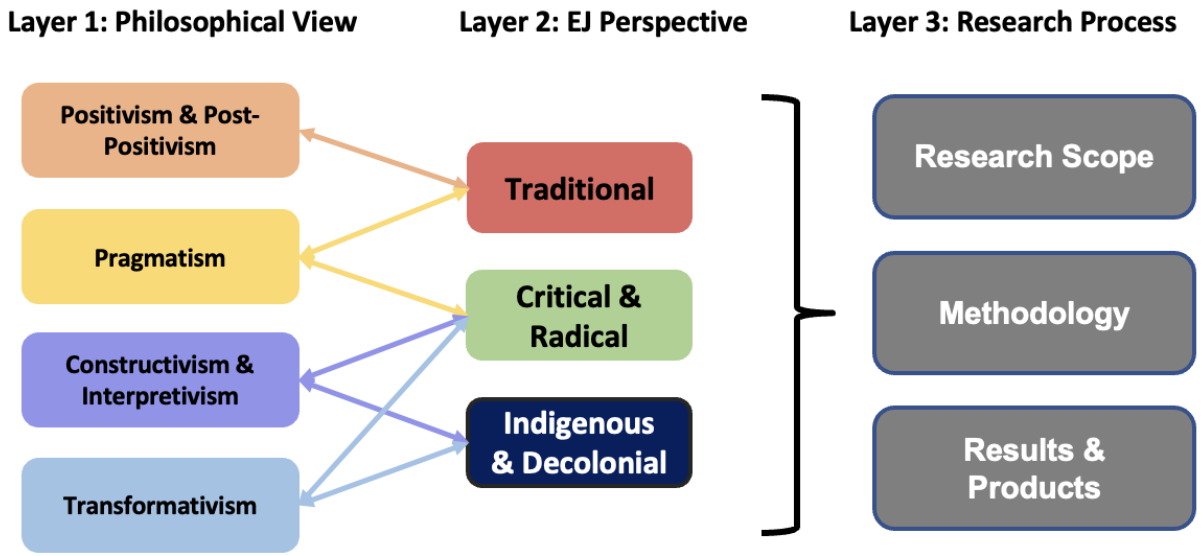


Fig 1. Flow Chart of Three Layers

3.1. Layer 1: Broader Philosophical Views

The first step for understanding collaborative potential between S&E and EJ research is to clarify what these disciplines consider "knowledge."[61,62] Awareness of our (often implicit) assumptions about the nature of knowledge and explanation is essential for interdisciplinary collaboration. A significant body of literature on the philosophy of science – ontology (what constitutes reality) and epistemology (how we generate and justify knowledge) – has connected our understanding of reality to our selection of research methods.[61–66]

We define philosophical views as premises with respect to what is considered knowledge and identify research methods associated with specific views. Diverse philosophical underpinnings cannot be directly compared because they resemble "incommensurable paradigms" that may not have common standards for measurement or evaluation.[15] They are typically derived from researchers' disciplinary training and experiences.[61,62,64,65] Table 1 outlines four paradigms that are particularly important for scientists and engineers to understand: positivism/post-positivism, pragmatism, constructivism, and transformativism.[61] S&E-related researchers can more easily collaborate within the first two paradigms, as post-positivism/positivism and pragmatism approaches relate to more applied, solutions-driven work within the boundaries of the current system and society in which we live. Meanwhile, constructivism is a context- and experience-based way of "knowing" the empirical world, and transformativism proposes that knowledge is not only contextual but is also shaped in relation to systems of power and legacies of inequities. These latter two perspectives tend to lead researchers to advocate for more structural changes that S&E-related researchers might not be inclined to pursue. We also note a few examples of EJ-related research that would fall under each philosophical view. Mayfield and Cushing et al. provide examples of positivist/post-positivist approaches to EJ-related research;[67,68] Baker et al. and Ohayon et al. give examples of pragmatic EJ research;[69,70] Dory et al. use a constructivist philosophical view to EJ research;[71] and Pulido & de Lara and Álvarez & Coolsaet embody transformativist approaches to EJ research.[53,60] As indicated by Fig. 1 and because of incompatibilities in approaches to knowledge, we connect the following layers: positivism and post-positivism are mainly compatible with traditional perspectives; pragmatism is primarily compatible with traditional and critical/radical perspectives; and constructivism and transformativism are most compatible with critical/radical and Indigenous/decolonial perspectives in layer 2.

Philosophical View	**Key Attributes**
Positivism & Post-Positivism[61,65,66]	● Based on existence of objective reality (post-positivism acknowledges that human observation and measurement are always subjective) ● Quantitative experiments & scientific method (ex: causal relationships between variables) ● Survey and interview methods that seek "data" rather than perspectives ● Aims for objective and value-free knowledge ● Typically science, technology, engineering, and mathematics-related fields; also some social sciences
Pragmatism[61]	● Scopes and questions defined by problem researchers trying to solve in current political, social, economic moment ● As-needed methods (mixed-methods including quantitative and qualitative) ● Pluralistic approach to philosophical views and differences

Constructivism[61,64–66]	• Understands that people perceive realities and validates lived experiences and social interactions as knowledge • Direct refutation of positivist and post-positivist ideas • Qualitative research methods only
Transformativism[61]	• Recognizes that traditional science (and research) silences voices of marginalized and oppressed communities • Critiques current power structures, including the state • Aims to elevate knowledges based on race, gender, disability, and Indigenous positionalities

Table 1: Four Philosophical Views Modified from Creswell & Creswell[61]

3.2. Layer 2: EJ Perspectives

We define perspectives as the stances taken within the EJ literature on how to define injustice or mechanisms of redress: What is justice? Who is marginalized and whose life do we value? Whom should we turn to for redress? We present three widely used perspectives: traditional, critical and radical, and Indigenous and decolonial. These perspectives have been applied to different contexts and problems beyond EJ research, existing independently of the scope provided below, but we define these here in the context of the lens brought into EJ research. We separate critical/radical from Indigenous/decolonial because, though they share some common themes in problem identification and solution, they arise from very different histories and positionalities. Indigenous and decolonial perspectives also have important differences, but we group them together because they share the premise of coloniality (inequalities stemming from internal or external colonization) as the root of persistent injustices.

Traditional:

1. **Origin:** The contemporary EJ movement in the U.S. is often said to be sparked by the 1982 North Carolina government's dumping of polychlorinated biphenyls in Warren County, building off the Houston Waste Study in the 1970s, although the movement existed informally prior.[5,54] This is still the mainstream strand within EJ and is popular with quantitative researchers in disciplines such as public health, engineering, and several social sciences.
2. **Problem Identification:** Research questions focus mainly on the establishment and/or measurement of disparate allocation of resources (or harms) across communities and over time.[6,7,54,72,73] Procedural justice and the legal struggles of under-served communities are also important. Traditional EJ is anthropocentric.[7]
3. **Problem Solutions:** Traditional EJ approaches may analyze how injustices have historically occurred, but injustices are approached as bounded problems that can/should be resolved by state intervention.[7] Possible forms of redress follow the three types of justice through funding allocation, agencies and bureaucratic institutions, laws and policies, and court cases.[7,8]
4. **Research Examples**: Metrics and measurements have dominated the academic EJ literature since the 1990s and still represent a significant body of literature. In the 1990s, influential studies were conducted on whether EJ was a race or class issue, and whether waste or power plants were intentionally built in places where marginalized groups lived.[2,6,74–81] More recent examples from the 2010s and 2020s include analyses on disproportionate air pollution impacts, equitable fossil fuel retirements, and just energy transition planning.[67,68,82–91]

Critical/Radical:

1. **Origins:** Critical perspectives reject the normalization of power hierarchies and injustices arising from capitalism.[92] Critical EJ (CEJ) – formalized by David Pellow in the mid-2010s – goes beyond investigating disparate impacts, focusing on the systematic structures that keep communities vulnerable regardless of

instances of movement success.[7,50] Critical work is usually conducted by qualitative social science disciplines.

2. **Problem Identification:** Pellow's four pillars of CEJ are: intersectionality, because modes of marginalization can build upon each other; multi-scalar analyses, so injustices can be addressed from local to global levels; critiques of the state in perpetuating (rather than mitigating) injustices; and expendability, or the tendency to view certain populations, especially non-human species, as disposable when we consider the value of life.[7]
3. **Problem Solutions:** While critical and radical theory have similar perspectives in problem identification, they diverge around solutions. CEJ calls for the ending of oppressive connections with state structures that de facto perpetuate injustices but does not demand the dissolution of the state itself.[7] Radical perspectives extend beyond critiquing the state, often in non-academic environments, offering suggestions around dismantling the state and prioritizing grassroot movements' actions.[93]
4. **Research Examples:** Sze traces the histories of Standing Rock protests against the Dakota Access Pipelines and the water crisis in Flint, Michigan to understand how these situations occurred, highlighting the roles of neoliberalism and expendability. Sze emphasizes the centering of culture and life over extractive industries in her proposals for restorative justice.[9] Pulido's work attributes the horrors of the Flint water crisis to racial capitalism and shows how the poisoning of devalued lives continued over years.[51]

Decolonial and Indigenous theorists have argued that both traditional and critical EJ concepts dominate current research practices, while Indigenous and decolonial EJ represent politics and perspectives that are rooted in colonizing and colonized experiences, and that are not as central in the other two approaches.[52,57]

Indigenous & Decolonial:

1. **Origins:** Decolonial perspectives originate from scholars in the Global South, especially Latin America and Asia, differentiating themselves from ideas originating from the Global North.[60,94] History, anthropology, sociology, philosophy, and geography are academic disciplines where these perspectives may be expressed.[53]
2. **Problem Identification:** Indigenous and decolonial theories question the relevance of research and co-production that originate from liberal-leaning political philosophies.[57,60,95,96] Both argue that persistent inequalities arise from internal or external colonization of Indigenous resources and value systems, and that even dominant critiques of anthropocentric "nature" and capitalistic "development" neglect this premise.[53,92,94,97] McGregor argues that natural resources are not commodified in Indigenous theory; rather, Earth itself is considered a living being.[52] The state is often framed as "settler colonial" (referring to colonizers who settle on the land rather than extract from it).[52,57,73,98–100] Decolonial EJ work in particular seeks to remove coloniality from resource management practices.[60,94,95,100–103]
3. **Problem Solutions:** Just solutions require Indigenous people and marginalized communities across the Global North and South, their knowledge, and their histories of violence to be prioritized and recognized to shape what "justice" means within EJ.[52,57,73]
4. **Research Examples:** Estes investigates the #NoDAPL (No Dakota Access Pipeline) movement to prevent the building of a major oil pipeline through the Standing Rock Sioux Tribe, focusing on the meaning of Indigenous resistance to settler colonialism and capitalism.[104] Rodríguez and Inturias investigate narratives and institutions in Latin America where grassroots movements (for example, the Water War in Bolivia) employed organic strategies for resistance and challenged existing institutions that reflected modes of coloniality.[95]

3.3. Layer 3: The Research Process

Research projects vary by genesis, methods used, anticipated impacts, and modes of dissemination. These aspects are usually derived from the perspectives and philosophical views upheld by the researcher and must be understood when building interdisciplinary teams. In Table 2, we link the perspectives of layer 2 with the processes of layer 3 to summarize how differences in perspectives result in varying outcomes in research projects from genesis to dissemination. Table 2 indicates where potential for and challenges of collaboration can occur for S&E scholars and condenses discussions in the following subsections. From the analysis in this section, we conclude that S&E scholars have the greatest avenue for collaboration with traditional perspectives, some possibilities for collaboration with critical and radical perspectives, but relatively few opportunities to engage with Indigenous and decolonial perspectives.

Research Genesis:
We define research genesis as 1) posing the research question(s), 2) determining collaborators, and 3) obtaining funding. All components are related to what constitutes "research" in each discipline or perspective.

Perspectives from layer 2 drive how problems are formulated and identified, which shapes the prospects for cross-disciplinary collaborations. The row "Research Genesis" in Table 2 summarizes common objectives and approaches to justice-related questions by perspective. Table 2, row "Compatibility for S&E Collaborations," shows that the clearest avenues for collaboration occur within the same perspectives because research genesis and methods are epistemologically compatible with one another. Nonetheless, opportunities for S&E researchers to partner across different perspectives exist.[96,105,106] For example, Liboiron et al. study plastics in Inuit Nunangat to characterize and compare the concentration of plastics to nearby Arctic regions and analyze injustices and implications of colonialism on the research process.[105] The quantitative approaches that researchers used to collect data about the processing of the plastics exemplified traditional methods. However, because this study encompassed a collaboration across traditional, Indigenous, and decolonial perspectives, the discussion focused on "reconciliation science," where authors explicitly elaborated on how permits were conducted, how collaborators were finalized, how research processes can create more waste, and who has historically benefited from this type of work. The Liboiron et al. study indicates that, despite epistemological compatibility between S&E research and the traditional perspective, it is possible for S&E scholars to collaborate with scholars with Indigenous and decolonial perspectives.[105] Such partnerships require explicit acknowledgement of epistemological differences to determine how best to negotiate these.

Researchers intentionally choose their collaborators, a process that both shapes, and is shaped by, the research question. Interdisciplinary work can arise ad hoc to fill missing perspectives in a research project (such as community beliefs about water contamination in an exposure study) or as a deliberate plan to include diverse viewpoints and collaborators. The willingness of researchers to acknowledge the value of different philosophical views determines how easily they can form impactful collaborations. The open-mindedness of researchers can be as important an influence on the potential to collaborate as their perspective similarities.[107]

S&E collaborations can take place with EJ scholars and also with EJ communities. Collaboration with community members is also tied to the prioritization of knowledge sources and methods. Community engagement within traditional perspectives usually involves observations or interviews, but decolonial and Indigenous perspectives cultivate deeper collaborations. Two approaches to community involvement that have changed interdisciplinary EJ research are: 1) community-based participatory research (CBPR), and 2) the two-eyed seeing approach. CBPR is a collaborative approach where the goal is to involve community members, researchers, and other parties as expert partners in every step of the research process.[108,109] Extensive work has also analyzed the tensions and possibilities of academics (often S&E scholars) engaging well in community-based work.[110,111] The two-eyed seeing approach aims to open minds to understanding Indigenous and traditional science, acknowledging ontological differences between these, but enabling researchers to explore both perspectives.[112]

We lastly note that funding acquisition for scientists and engineers is related to the EJ perspectives through the research genesis and the chosen collaborators. Some perspectives are more attuned to particular methods, and some methods are more likely to be competitive when seeking research funding.[113–116] Beliefs on the role of the state for addressing injustices may also impact funding for projects.

Research Methodology:
Perspectives shape method selection, which we here define as data collection and processing. First, data collection in the research process is dictated by the perspective, particularly related to whose knowledge is included. Embodying certain perspectives guides researchers towards specific data types, but this does not prevent them from collaborating on data collection or evaluating combined data sources. Second, data processing, by which we mean using qualitative, quantitative, and mixed methods, are determined by the research question, but the extent of a researcher's expertise in these methods delimits the project scope. Quantitative methods include statistical methods, geospatial analyses, optimization and coding tools, and epidemiological studies. Qualitative methods include participant observation and ethnography, narrative analysis, interviews, and qualitative content analysis.[117–120] Traditional EJ perspectives may prioritize measurements and quantitative models but also use qualitative methods. Meanwhile, critical, radical, Indigenous, and decolonial perspectives tend to highlight the voices of marginalized populations via CBPR or two-eyed approaches, leaning significantly on qualitative methods.

Alignment of data collection and processing methods makes collaboration across perspectives easier. As outlined in the row "Methods" and the row "Compatibility for S&E Collaborations" of Table 2, S&E researchers are more aligned with methods associated with traditional perspectives because of the strong overlap in quantitative methods. Collaborative S&E opportunities with critical, radical, Indigenous, and decolonial perspectives may be more difficult to build given some disagreements over methods and data (linked to whose knowledge is prioritized). In these contexts, working with mixed methods in sequential order within a multi-part project is possible and can improve the robustness of results. For instance, Liboiron et al. and Nsude et al. rely on heavily traditional approaches to science and data analysis in establishing EJ-relevant impacts. However, in the discussion sections of both papers, when interpreting the significance of their frameworks and findings, they respectively reference historical legacies of colonialism in science and CEJ.[29,105] These papers show that there does not have to be perfect alignment on methods used in cross-perspective collaboration, but the interpretation of results opens pathways for collaboration and opportunities for richer debates into the value of certain projects and research avenues.

Results and Products
Researchers make choices on how to present and format results for the intended audience (see Table 2, row "Results & Products"). Traditional perspectives may not mention redress, or they may prioritize asking the state for redress and present results to regulatory agencies, policymakers, and/or lawyers. Meanwhile, other perspectives may disagree on the role of the state as an audience, favoring activists, community members, or other academics. This difference leads to a natural grouping of perspectives: traditional and critical EJ perspectives, on the one hand, and Indigenous, decolonial, and radical perspectives on the other. Traditional perspectives tend to seek solutions to injustices within the governing structures of the state and are led by state interventions, while sometimes acknowledging criticisms of the state. Critical perspectives call for structural changes of the state or for outside-the-state redress possibilities, while radical approaches may demand the entire dismantling of the state. Indigenous and decolonial perspectives tend to reject the notion of engaging with the state. However, radical, Indigenous, and decolonial approaches can still be useful to researchers mainly using traditional methods, as these perspectives can change how researchers think about approaching research problems and question the assumptions behind these approaches.

Selection of audience also affects how scholars choose to present their results. Research output can be expressed as journal papers, books, policy briefs, information distributed to communities, court case evidence, etc. Collaborative

efforts across disciplines can lead to multiple publications that engage with more than one perspective. For example, scholars may publish quantitative study results based on a traditional perspective and later publish work based on critical perspectives on how societal structures drive these injustices to arise and persist. The opportunities to write a series of products enable academics to reach myriad audiences and support challenging, cross-perspective collaborations. For example, in the case study below, a series of research papers were published, highlighting scientific findings of occupational hazards for female firefighters and underscoring the importance of CBPR approaches.[69,121–123] Beyond the papers published, Ohayon et al. discuss how their work was presented in other formats. Researchers supported firefighters presenting at peer firefighter conferences, helped with training workshops at firehouses across the U.S., and introduced study results to state policy and international proceedings.[69] This case study uses a traditional perspective but promotes interdisciplinary collaboration to provide redress recommendations to the state.

	Traditional	**Critical/Radical**	**Indigenous/Decolonial**
Research Genesis	-**Main objectives:** establishment (or not) of distributive injustices in study sites with implicit or explicit assumption of state partnership -**Target Impacts:** Anthropocentric impacts only -**Types of justice:** mainly distributional, followed by procedural justice -Increasing interest in CBPR and two-eyed approaches	-**Main objectives:** capitalism and historical causes of injustices; extends beyond analyses on race and class (ex: gender, disability) -**Target Impacts:** Human and/or non-human life impacts -**Types of justice:** distributional, procedural, recognitional, and restorative justice -Established body of literature on CBPR approaches	-**Main objectives:** impacts (and potentially methods) situated historically as consequences of capitalism and/or colonialism; emphasis on communities most affected by settler colonialism or coloniality -**Target Impacts:** Human life, non-human life, and ecological change impacts -**Type of justice:** possibility of distributional, procedural, and recognitional justice (recognition as foundation of all injustices); some pushback on traditional framework of injustices -Established body of literature on CBPR and two-eyed approaches
Methods	-**Mainly quantitative methods** (sometimes includes qualitative methods) -Usually quantitative data collected with little to no prioritization of community knowledge or two-way learning (prioritization of community knowledge is increasing and changing)	**-Qualitative and mixed methods** -Prioritization of community knowledge via CBPR approaches	**-Qualitative and mixed methods; history is central** -Prioritization of community knowledge -Some engagement in both CBPR and two-eyed approaches
Results & Products	-**Findings may not address redress** or may implicitly/explicitly call for redress by state -**Audience:** government, academia, private sector,	-**Findings aimed at specific communities or local learning**; may implicitly/explicitly call for solutions by non-state entities	-**Findings aimed at activist alternative to state structure** -**Audience:** activists, lawyers, academia

	lawyers, nonprofits, activists	-**Audience:** activists, academia, government, lawyers	
Compatibility for S&E Collaborations	-**Strong compatibility** on research questions & genesis, definition of knowledge, methods, interpretation of results -**Default quantitative methods** are often enriched or informed by qualitative methods -**High feasibility for collaboration** and agreement on (almost) every aspect of research process	-**Some compatibility** on research questions & genesis, definition of knowledge -**Possible conflicts** on methods and interpretation of results -**Feasible but complex to collaborate**, especially on interpretation of results and research scope	-**Potential incompatibilities** on research questions & genesis, definition of knowledge, methods, interpretation, or explanation of results -**Greater difficulty** in S&E collaboration on methods or interpretation of results than critical and radical initiatives -**Possible but difficult to collaborate** on explanation of problem origin or interpretation of results
Examples of S&E Collaboration	(Balazs et al.; Karasaki et al.)[33,124]	(Baker et al.; Nsude et al.)[29,70]	(Chief et al.; Clausen et al.; Liboiron et al.; Liboiron et al.)[96,105,106,125]

Table 2: Influences of Perspectives (Layer 2) on the Research Process (Layer 3)

4. Case Study: Occupational Exposure to Hazardous Substances in a Cohort of Women Firefighters and Office Workers in San Francisco

Interdisciplinary collaborations that advance environmental justice tend to share some of several common features: they recognize epistemological differences across disciplines, integrate multiple forms of knowledge into the research process, and meaningfully engage the communities affected by environmental harms. The case study was chosen specifically as an example of interdisciplinary S&E work that engages with all three features and to be analyzed by the proposed framework. We view this case study and the case study in supporting information (SI) as illustrative examples of how to conduct interdisciplinary S&E EJ research because of how the respective research teams either incorporated other research disciplines and community knowledge to expand the scope of their justice impacts or designed their research to be interdisciplinary to accommodate other forms of knowledge in their pursuit of justice goals (case study in SI). Table 3 provides a summary of findings for this case study (we provide a similar analysis for the case study in the SI).

The case study focuses on a constellation of papers that investigate firefighters' occupational exposure to perfluoroalkyl substances (PFAS) and flame retardants.[69,121–123] A health survey within the San Francisco Fire Department in 2012 revealed that women firefighters had elevated breast cancer rates compared to the average population. This is an example of an environmental injustice by the definition listed in Section 2, as female firefighters are disproportionately exposed in their work environment to cancer-causing substances. Firefighter advocacy organizations partnered with academic institutions (UC Berkeley and the Silent Spring Institute) to form the Women Workers Biomonitoring Collaborative (WWBC) to uncover potential environmental and occupational causes of breast cancer.[69]

The WWBC recruited women firefighters and office workers (as a control group), collected data on the occupational history of participants and biospecimens (urine and blood), and disseminated research results to study participants, the broader firefighter community, and decision-makers. The WWBC published academic papers on the link

between firefighter duties and exposure levels to multiple compounds, and their association with upstream biomarkers of effect of relevance to cancer. This work also contributed to policy changes, including updates to presumptive workers' compensation laws to include breast cancer in California and Massachusetts; improved practices related to fire station decontamination; bans on PFAS in firefighting foams; and the development of the first known biospecimen archive for women workers.[69]

We classify the study as pragmatic (Layer 1) because it used mixed methods to achieve specific goals, i.e., targeted changes to procedural and distributional justice in the firefighting industry to protect women's health. While the academic publications centered on rigorous statistical analyses, qualitative inputs such as focus groups were essential in initiating the study, developing research tools, and ensuring rigorous collection of high-quality biospecimen data. The study embodies a traditional perspective (Layer 2) because it acknowledges women's exclusion from state benefits due to legacies of gender discrimination, but nonetheless expects state agencies to implement reforms leading to distributive justice. The CBPR methods aligned with biomonitoring data (Layer 3) yielded multi-faceted research outcomes by co-creating knowledge among researchers and firefighter collaborators. Firefighters presented scientific results at major conferences, worked in the lab, developed research participant questionnaires, interpreted data analyses, and co-authored scientific articles.[69]

Three features of this work stand out as considerations for future studies. First, qualitative methods were integrated with quantitative analysis of biomarkers of exposure and effect in a way that demonstrated and positively conferred authority on two distinct epistemologies. Qualitative information elicited from women firefighters initiated the study and provided the impetus to recruit S&E expertise towards new biomonitoring data and methods. Second, the community's initiative substantially widened the reach of distributional and procedural justice outcomes. Women firefighters and advocates invited S&E researchers to generate credible data and analyses to characterize chemical exposures and their relationship to biomarkers of effect pertaining to breast cancer. CBPR works to incorporate multiple perspectives,[30] and Ohayon et al. highlight the importance of the mutually supportive objectives that sustain this ongoing collaboration.[69] We note, however, that many marginalized communities lack comparable capacities or institutional backing to benefit from CBPR. Third, the partnerships yielded results and impact within three years, but this may be an impractical timeline for distressed communities and for researchers who are under publication pressure. Given that sustained relationship-building is a defining feature of CBPR, researchers should account for the extended timeframes often necessary to cultivate these partnerships.

	Occupational Exposure to Hazardous Substances in a Cohort of Women Firefighters and Office Workers in San Francisco
Research Summary	Community-initiated investigation of occupational hazard exposure for women firefighters in San Francisco[69,121–123]
Academic Discipline	Environmental toxicology
Layer 1: Philosophical View	Pragmatic; Research is focused on the goal of demonstrating how occupational hazards and structural inequities lead to increased rates of breast cancer in women firefighters
Layer 2: EJ Perspective	Traditional; Meaningful collaboration between the fire department, firefighters, environmental groups, and academic institutions to provide the modes of redress to resolve structural inequalities for women workers
Layer 3: Methods	Qualitative semi-structured interviews and focus groups to inform individual and aggregate results return; quantitative longitudinal biomonitoring to analyze exogenous and endogenous chemicals to characterize early adverse effects of

	exposures
Layer 3: Research Scope	Can one find a quantifiable link between occupational duties in the fire service and exposures to potential mammary carcinogens; does one observe associations between chemical exposures and biomarkers of effect of relevance to breast cancer? How can one best translate results for policy change to reduce chemicals in firefighting foams and improve industrial hygiene standards in firefighting?
Layer 3: Results & Products	● Community members (firefighters) actively participated in development of study design and grant writing to implement interdisciplinary research design ● Resulting collaboration provided evidence for shifting presumptive workers' compensation laws in various states to include breast cancer and for banning PFAS in firefighting foams in California ● Qualitative and quantitative data helped advance improvements in safety protocols for firefighters at the local, state, and national levels ● Led to the creation of the first biospecimen archive for female workers and established the Women Worker Biomonitoring Collaborative that has expanded work to other female occupational groups (nurses, domestic workers, hospital workers, home health care aids and office workers)

Table 3: Case Study Summary & Overview

5. A Path Forward for Interdisciplinary Environmental Justice Research

Differing positions on how to create knowledge and enable change – fueled by the epistemological differences in approaches to research across academic disciplines – shape how EJ research is framed across disciplines. Multiple disciplines are often needed to solve complex problems, but epistemic and methodological divides hinder constructive collaborations. In this perspective, we present a three-layer schematic and a case study in the EJ literature to highlight barriers to, as well as opportunities for, EJ-relevant collaboration for S&E researchers.

The first layer focuses on broader philosophical views, which determine how researchers conceptualize knowledge and understand the research enterprise. We find that a capacious approach to knowledge formulation can allow scholars to broaden their views, work across epistemic boundaries, and increase the transformative potential of their work. In the second layer, we tie these underlying philosophies into more or less compatible EJ perspectives: traditional, critical and radical, and Indigenous and decolonial, for readers to identify how philosophies and perspectives work together to develop research designs. In Layer 3, we focus on how these perspectives translate into various stages and methods of the research process, and on understanding which differences can be overcome using interdisciplinary efforts and which remain more intractable. Specifically, we show that S&E researchers can most easily work with epistemologies and methods usually associated with traditional perspectives (Table 2) but need to be more methodologically flexible if they want to work with scholars within critical/radical EJ or with decolonial/Indigenous scholars.

The case study represents an example of interdisciplinary EJ research that successfully bridges different disciplinary approaches by spanning diverse views, perspectives, and methods. This example is intended to orient engineers and scientists who are interested in collaborative work on EJ to the possibilities of interdisciplinary research.

In this perspective, we have not posited a single definition of "ideal" or even "successful" collaboration. Rather, we find that collaboration can take shape at many levels, from bringing scholars into projects based on needs of the research question to intertwining methodological approaches and co-designing studies together across disciplines. Successful collaboration will depend on the scholars involved and objective of the project. To that end, we propose

four recommendations. First, scholars should explicitly acknowledge their own epistemological and philosophical views, which implicitly shape their research conduct from project genesis to analysis of results and presentation of outcomes. Second, researchers should seek to understand how their views may differ from other disciplines. Understanding one's own and others' philosophical views (and blind spots) is a prerequisite to effective interdisciplinary S&E collaboration. Third, we encourage scholars to learn more about the history and evolution of their disciplines to understand the origins of the underlying values and methodological assumptions that shape how research is conducted in their fields. Elucidating why specific questions and assumptions are central to one's own field denaturalizes them, which in turn can facilitate more productive engagements with other fields with different premises. These understandings help to determine what methods, models, and tools to draw from diverse disciplines that undertake EJ research. Lastly, researchers can learn from existing academic projects that address environmental justice challenges, including but not limited to AGU Thriving Earth Exchange, GeoHealth, and Project Confluence.[111,116]

We recognize that interdisciplinary work has logistical barriers that need to be overcome before initiating projects. Collaboration takes time and effort, as scholars need to understand other viewpoints not similar to their own. Different conventions across disciplines on how often to publish, mode of publication (conferences, journals, books), and willingness to work with communities on their terms complicate opportunities to collaborate. Incorporating perspectives outside of what is common within S&E can potentially alter the framing or meaning of results, which should not be seen as a dilution of the "science" but as an awareness of the histories and cultures within which the results and the science must make sense. The case study showcases the value and importance of interdisciplinary EJ work across disciplines, particularly in the results and relevance it brings to practitioners, communities facing injustices, and novel approaches to interdisciplinary collaboration for researchers. We present the schematic in this paper as a signpost for EJ researchers pursuing collaborative projects that seek to address the pressing EJ issues that define our reality.

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Supporting Information Available

This information is available free of charge via the Internet at https://pubs.acs.org/doi/10.1021/acs.est.5c16364. An additional case study analyzed by the EJ schematic is included.

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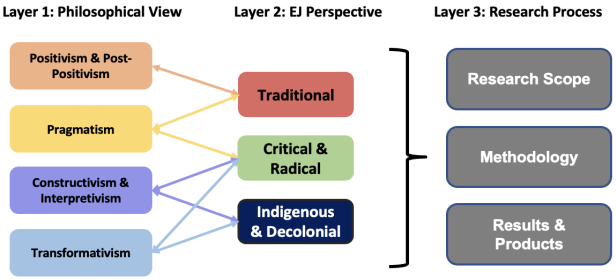
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Biography



Aneesha Manocha is a PhD student and NSF Graduate Research Fellow at the University of California, Berkeley in the Energy Resources Group. She works on developing optimization methods and macro-energy system models to plan decarbonized energy futures. More specifically, she researches how to prioritize historical environmental injustices in modeling frameworks. Aneesha was a Kanders Churchill Scholar at the University of Cambridge, receiving an MPhil in Public Policy with Distinction. She completed her undergraduate degree at Princeton University, majoring in Electrical and Computer Engineering.