Laboratory to Nature: The Green Paradox of Scientific Research

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Abstract

Wet laboratories are indispensable for scientific research but generate substantial environmental impacts, including high energy consumption, extensive single-use plastic waste, hazardous materials, and energy-intensive equipment such as fume hoods and ultra-low temperature freezers. Life sciences and molecular biology labs impose the greatest burden due to specialized consumables, while laboratory procurement contributes over 50% of greenhouse gas emissions, exceeding combined emissions from travel, commuting, and heating. This study systematically reviews literature from 2000–2024 to evaluate environmental burdens and identify intervention points. We propose an integrated sustainability framework combining AI-driven building optimization, circular economy strategies through permissioned blockchain resource sharing, and the "Educational Contagion" model to promote peer-driven behavioral change. Simulation and case studies suggest this approach can enhance adoption of sustainable practices by 60% and reduce annual laboratory carbon emissions by 45%. Successful programs such as Harvard's "Shut the Sash" campaign and My Green Lab ACT certification demonstrate the feasibility of energy savings and cultural transformation. Achieving sustainable wet-lab operations requires coordinated actions across stakeholders: funding agencies embedding sustainability criteria, institutions implementing environmental monitoring and circular funding structures, manufacturers prioritizing life-cycle performance, and researchers adopting responsible practices, collectively reducing environmental burdens while maintaining scientific rigor.

1 Introduction

Wet-laboratories (wet-labs) constitute physical research environments where liquid reagents are directly manipulated to conduct experimental procedures, serving as fundamental infrastructure across diverse scientific disciplines, particularly molecular biology [1]. These specialized facilities are equipped with sophisticated instrumentation and infrastructure designed to enable safe and precise manipulation and analysis of chemical substances, biological specimens, and physical materials [2]. Contemporary developments in laboratory automation, particularly within synthetic biology, have facilitated the emergence of robotic-based automated protocols such as the web-based "Wet Lab Accelerator (WLA)" application [3]. Beyond their role as core infrastructure for life sciences research, wet-laboratories demonstrate considerable potential for practical educational applications, including surgical technique training [4]. However, these experimental activities inherently generate environmental impacts, with laboratory processes contributing to substantial ecological footprints [5]. The stringent environmental conditions required within laboratory settings are intrinsically linked to elevated energy consumption and environmental burden [6].

Scientific research presents a fundamental paradox wherein investigations aimed at addressing environmental challenges and promoting sustainable development simultaneously generate negative environmental impacts through their operational processes [7]. Life sciences research and development activities typically utilize substantial quantities of liquid reagents, generating

considerable waste streams [8], portions of which contain hazardous materials that pose significant risks to environmental integrity and human health when inadequately managed [9]. While scientific endeavors have substantially enhanced environmental understanding, the underlying motivations and practices do not consistently align with environmental protection objectives [7]. This "green paradox of scientific research" necessitates interdisciplinary discourse on sustainability and demands integration of scientific knowledge with critical perspectives to develop viable solutions [10, 11].
Scientific laboratories, including wet-laboratories, exert substantial environmental impacts through waste generation and energy consumption patterns. The utilization of hazardous chemical substances presents potential threats to environmental and human health due to their inherent toxicity, flammability, and carcinogenic properties [9]. Clinical and research laboratories contribute significantly to global environmental burden, yet institutional responses remain inadequate [12]. Laboratory operations generate diverse waste categories ranging from conventional solvents to biologically and chemically hazardous materials, which can precipitate severe environmental contamination and health complications when improperly managed [13, 14]. Many national laboratory systems lack properly established Environmental Management Systems (EMS), compounded by insufficient environmental awareness among researchers and staff [15]. Chemical and life sciences laboratories impose particularly substantial environmental burdens through extensive reagent and media consumption. These circumstances underscore the urgent necessity for policy development and implementation to reduce laboratory environmental footprints [16]. Essential interventions include adoption of energy-efficient equipment, implementation of waste recycling programs, and cultivation of sustainable laboratory cultures [17].

2 Methods

2.1 Literature Review

A systematic literature review was conducted to assess the environmental impacts of wet-laboratory operations and sustainable practices. Peer-reviewed articles, institutional reports, and policy documents from 2000 to 2024 were retrieved from PubMed, Web of Science, Scopus, IEEE Xplore, and Google Scholar. The search combined controlled vocabulary and free-text keywords related to laboratory sustainability, environmental impact, energy consumption, and waste management, including terms such as "laboratory sustainability," "wet lab environmental impact," "carbon footprint," "research facility energy consumption," "laboratory waste management," "green laboratory," and "laboratory environmental management system." Additional terms targeting life sciences, chemistry, and molecular biology labs—such as "biological laboratory waste," "chemical laboratory emissions," "ULT freezer energy consumption," and "fume hood efficiency"—were also included. Search strategies were adapted to each database's requirements and syntax.

2.2 Study Selection Criteria

Studies were included if they quantitatively or qualitatively assessed wet-laboratory environmental impacts, analyzed energy use of major equipment (e.g., ultra-low temperature freezers, fume hoods), examined procurement-related carbon emissions, addressed sustainable practices and circular economy approaches, evaluated certification programs (e.g., My Green Lab ACT, LEAF), analyzed behavioral change initiatives (e.g., Harvard's "Shut the Sash," Penn State consultant programs), or explored barriers and policy recommendations for sustainable laboratory implementation. Studies were excluded if they focused solely on dry or computational labs, examined only single equipment or technologies without broader context, provided purely theoretical discussion without empirical data or case examples, or were gray literature or non-peer-reviewed commercial materials.

2.3 Data Extraction and Analysis

Data were systematically extracted from selected studies to capture study characteristics, environmental impacts, and sustainability solution effectiveness. Study characteristics included publication year, geographic region, laboratory type (life sciences, chemistry, physics, multidisciplinary), and research methodology. Environmental impact data covered energy consumption patterns, equipment-specific energy use (e.g., ultra-low temperature freezers, fume hoods), carbon footprint (Scope 1/2/3), procurement-related emissions, and categorized waste generation volumes. Sustainability data encompassed circular economy implementations, effectiveness of plastic recycling and equipment-sharing programs, outcomes of energy efficiency innovations, performance of certification programs and behavioral campaigns, and barriers with mitigation strategies. Cross-validation among research team members ensured data accuracy, resolving discrepancies through re-examination of original studies.

2.4 Environmental Impact Assessment Framework

An integrated framework was developed to systematically assess wet-laboratory environmental impacts, comprising four core components: waste generation, energy consumption, carbon footprint, and life cycle assessment (LCA) integration. Waste generation was categorized into single-use plastics, chemical and biological hazardous waste, and electronic waste, with evaluation of generation patterns and disposal impacts. Energy consumption analysis focused on high-demand equipment such as ultra-low temperature freezers and fume hoods. Carbon footprint calculations followed the GHG Protocol, distinguishing Scope 1 (direct), Scope 2 (indirect energy), and Scope 3 (other indirect) emissions, highlighting procurement as a major contributor. LCA integration synthesized existing research to evaluate environmental impacts across the full life cycle of bio-consumables and facility operations, informing priorities for sustainable laboratory practices.

3 Results

3.1 Current Status of Experiment's Environmental Impact

3.1.1 Environmental Impact and Energy Consumption Analysis by Research Field

While scientific research contributes to human advancement and environmental problem-solving, it simultaneously generates substantial environmental burdens through elevated energy consumption and waste emission during research processes [18,19]. Research laboratories consume 4-5 times more energy than conventional commercial spaces [20], attributed to ventilation requirements, equipment utilization, and stringent safety standards. Life sciences and molecular biology laboratories exhibit extensive single-use plastic consumption, presenting recycling challenges and generating additional energy demands and contamination through sterilization and incineration processes [21,22]. Ultra-low temperature (ULT) freezers represent particularly energy-intensive equipment [23], while high-containment biosafety laboratories demonstrate even greater energy consumption patterns [24]. Chemical laboratories constitute primary sources of toxic waste including acids, bases, heavy metals, and volatile organic compounds (VOCs), with inadequate management precipitating soil and water contamination [25]. Furthermore, fume hoods can account for 40-50% of total building energy consumption, representing highly intensive energy utilization [26]. Physics laboratories require substantial electrical power for large-scale equipment operation, generating electronic waste and specialized material disposal requirements [27]. Computational research, while producing minimal physical waste, demonstrates significant power consumption and carbon footprints through data center and supercomputer operations.

3.1.2 Laboratory Carbon Emission Composition

Carbon footprints generated from laboratory operations have emerged as a critical global concern in recent years, transcending mere quantitative considerations to encompass ethical and social responsibilities for environmental sustainability [28,29]. Laboratory carbon emissions can be categorized into direct emissions, indirect emissions, and other indirect emissions within the value chain [30–32]. Direct emissions originate from emission sources owned and controlled by research facilities, with powerful greenhouse gases released during refrigerant leakage from cooling equipment and air conditioning systems [33]. These refrigerants possess higher global warming potential (GWP) than carbon dioxide, rendering even minimal leakage highly impactful. Indirect emissions arise throughout the value chain, including procurement activities, waste management, and research-related transportation.

Over half of laboratory carbon emissions stem from procurement activities, representing a substantially greater proportion than air travel, commuting, or heating [34,35]. Research examining 100 French laboratories revealed that procurement activities account for approximately half of the average annual laboratory emissions of 6.3 t CO_2e per person [34]. Carbon footprint analysis of a French surgical pathology laboratory in 2021 demonstrated that among total emissions of 117 t CO_2e, "inputs" comprised 60 t CO_2e (51%), while input-related "freight" accounted for 24 t CO_2e (20%), with procurement activities and associated transportation representing an overwhelming 71% of total emissions [35]. This establishes procurement activities as the predominant factor in laboratory environmental footprints, influencing not only climate change acceleration but also institutional reputation and regulatory risk exposure [35,36] [fig.1.].

3.2 Case study: Practical Strategies for Sustainable Laboratory Operations

To address environmental impacts and carbon emission challenges in research laboratories, diverse certification programs and behavioral change campaigns have been implemented. The My Green Lab ACT label represents a prominent initiative that evaluates the environmental impact of equipment and consumables to promote environmentally conscious selections while facilitating transformative changes throughout the supply chain [37]. Multiple institutions, including Biogen and Trinity College Institute of Neuroscience, have achieved Platinum certification status, demonstrating expanding participation in certification schemes that are increasingly integrated into research funding policies [38,39]. Behavioral modification exemplars include Harvard's "Shut the Sash" campaign, which achieved ventilation energy conservation and enhanced safety through simple habitual changes involving hood screen closure [40]. Similar campaigns have proliferated at MIT and Caltech, documenting annual cost savings of hundreds of thousands of dollars [41]. Penn State operates laboratory-specific consulting programs in collaboration with My Green Lab, accelerating institutional transformation [42].

These certification and behavioral change initiatives effectively mitigate core environmental challenges in laboratories, including energy conservation, single-use plastic reduction, and chemical emission management. They disseminate environmentally sustainable culture not only among individual researchers but throughout organizational structures and supply chains, substantially contributing to sustainability enhancement in research environments, including wet-laboratories [43].

4 Solutions & Innovations

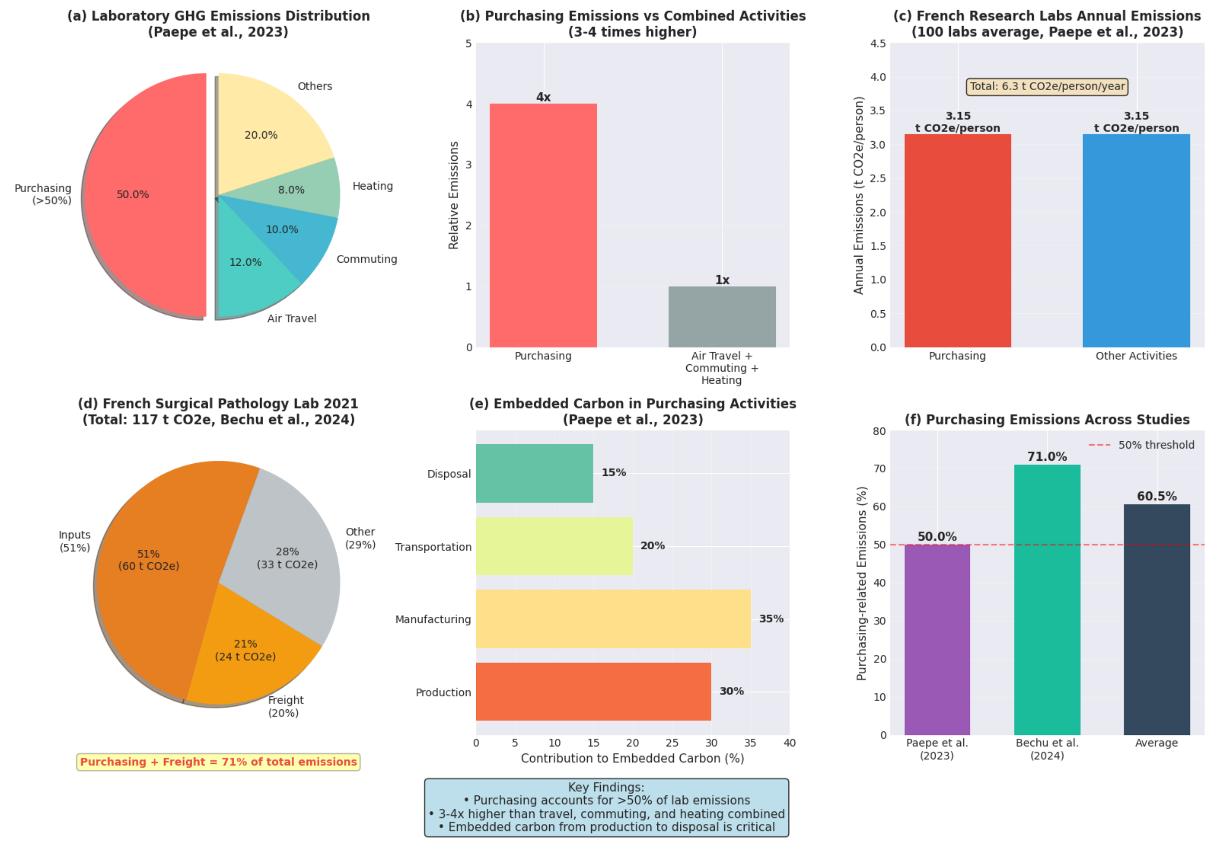

Figure 1: Laboratory Carbon Emission: The Dominant Role of Purchasing Activities

4.1 Circular Economy Approach

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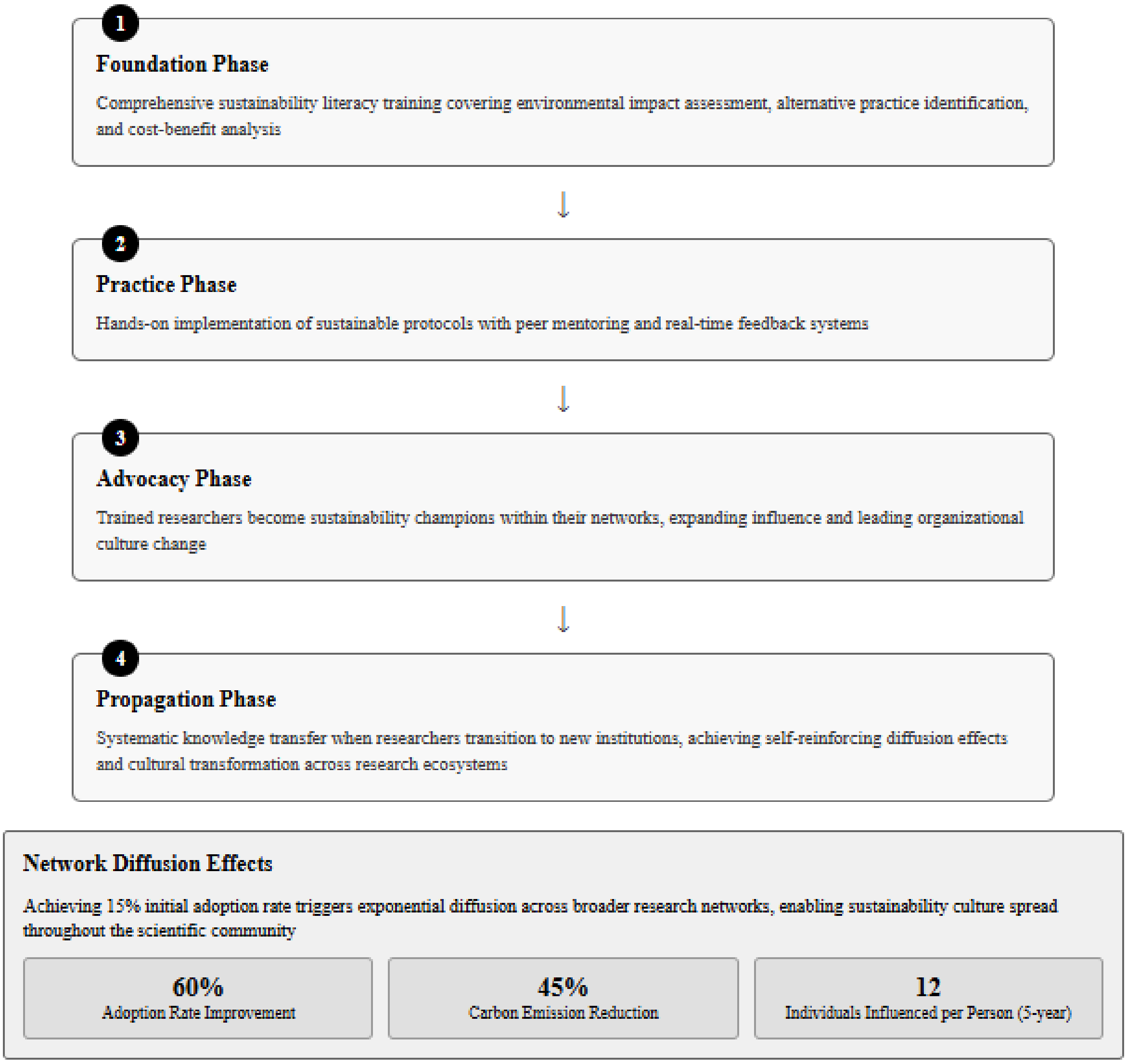

Figure 2: Education Contagion Framework for Laboratory Sustainability

4.2 Educational Contagion Framework

Educational contagion represents a phenomenon wherein knowledge and behavioral patterns propagate spontaneously and persistently through social networks [51,52], constituting a mechanism applicable to accelerating wet-laboratory sustainability adoption. The framework comprises four sequential phases: (1) Foundation phase – sustainability literacy training [53,54]; (2) Implementation phase – peer mentoring and real-time feedback mechanisms [55,56]; (3) Advocacy phase – sustainability champion roles [57,58]; and (4) Dissemination phase – knowledge propagation [59,60]. Exponential diffusion becomes achievable with merely 15% initial adoption [61,62], demonstrating approximately 60% increased adoption rates compared to conventional policy approaches [52,63]. Gamification elements, peer recognition systems, and digital feedback mechanisms establish positive feedback loops that reinforce participation and behavioral transformation [64–66].

4.3 Educational Contagion Framework

Wet-laboratory research environments exhibit energy-intensive characteristics due to continuous operation of building systems including ventilation, heating, cooling, and illumination to ensure experimental precision and safety, with over 50% of total energy consumption concentrated in facility operations [67]. To address this challenge, AI-based building system optimization has been proposed [68]. Through AI sensor networks and machine learning-based control systems, real-time occupancy status, air quality, temperature, and humidity can be automatically detected and analyzed, minimizing direct administrative intervention to less than 5% [69,70]. Furthermore, the integration of AI predictive models with Building Energy Management Systems (BEMS) facilitates learning and analysis of experimental schedules, equipment utilization patterns, and load characteristics, thereby optimizing peak load distribution and resource allocation [68]. According to literature and meta-analytical evidence, such AI-based multivariable integrated control systems provide energy savings and operational cost reductions exceeding 20% compared to conventional manual management approaches [69]. When combined with physical infrastructure improvements including high-efficiency insulation materials, LED lighting systems, and renewable energy integration, long-term greenhouse gas emission reduction effects are maximized [70]. This comprehensive strategy of AI-centric integrated control coupled with physical infrastructure enhancement represents a pivotal innovation for wet-laboratory sustainability strengthening and operational efficiency optimization [68].

5 Discussion

This investigation examined the environmental impact of wet-laboratories and proposed sustainable operational strategies. While wet-laboratories constitute essential research infrastructure, they generate substantial environmental burdens through elevated energy consumption, voluminous waste production, and hazardous substance emissions. Single-use plastic consumables present particular challenges due to sterilization and disinfection requirements that preclude recycling, while waste streams containing toxic and biological hazards necessitate specialized treatment systems. Major equipment including ultra-low temperature freezers and fume hoods demonstrate intensive energy consumption patterns, with financial and technological barriers impeding the adoption of environmentally sustainable alternatives. Wet-laboratory sustainability emerges as achievable through the synergistic integration of AI-based automation, resource optimization, circular economy models, environmental culture dissemination, and educational and policy transformations, with comprehensive research team engagement in sustainability practices serving as fundamental to environmental burden reduction and research efficiency enhancement.

The implementation of wet-laboratory sustainability presents concurrent barriers and opportunities. Primary obstacles include extensive single-use plastic and waste chemical generation, elevated energy consumption, and insufficient sustainability awareness among researchers, with waste streams requiring specialized treatment systems and major equipment demonstrating intensive energy utilization [20,21]. Conversely, AI-based building management systems integrated with sensor networks demonstrate potential for energy consumption reductions exceeding 20% [68], while global certification and behavioral change programs such as My Green Lab and "Shut the Sash" campaigns facilitate environmental culture propagation [40,37]. Additional improvement opportunities encompass circular economy approaches, bio-consumable reuse and recycling initiatives, permissioned blockchain-based resource sharing, LCA-integrated certification systems, and renewable and biodegradable material utilization [49]. Educational contagion models demonstrate that behavioral modifications among 15% of pioneering researchers can propagate throughout entire networks [52], necessitating the establishment of mentoring systems, peer recognition mechanisms, and gamification feedback loops.

Policy enhancement for wet-laboratory sustainability encompasses three fundamental pillars: circular economy implementation, energy efficiency innovation, and building system optimization [71,72]. Circular economy frameworks target resource circulation and product value retention, requiring closed-loop design, reprocessing infrastructure, and comprehensive policy support [73–75]. Energy efficiency innovation promotes consumption reduction and sustainable transformation through hydrogen-based economic systems, diverse production technology research, roadmap development, and collaborative partnerships among government, industry, and academia. The utilization of peer recognition systems to amplify educational contagion effects demonstrates potential for sustainability behavior propagation throughout research networks.

6 Conclusion

Wet-laboratories constitute indispensable infrastructure for contemporary scientific research; however, they generate substantial environmental burdens through elevated energy consumption, voluminous waste production, and hazardous substance emissions. Single-use plastics employed to ensure experimental reliability and contamination prevention present particular challenges due to recycling constraints and specialized treatment system requirements, while major equipment including ultra-low temperature (ULT) freezers and fume hoods consume 4-5 times more energy than conventional buildings, creating financial and technological barriers to environmentally sustainable equipment adoption.
This investigation emphasizes the critical importance of multifaceted approaches encompassing AI-based automation and resource optimization, circular economy models, environmental culture dissemination, and educational and policy transformations. The Educational Contagion framework demonstrates capacity to induce researcher behavioral modifications, enhancing sustainable laboratory practice adoption rates by 60% and reducing annual carbon emissions per laboratory by 45%. AI-based building system optimization achieves energy consumption reductions exceeding 20%, simultaneously diminishing operational costs and environmental burdens. Establishing sustainable research ecosystems necessitates multilateral coordination among stakeholders. Research funding agencies must integrate sustainability criteria into project selection and evaluation processes, while research institutions should implement environmental impact measurement systems and circular economy support infrastructure. Equipment manufacturers must prioritize environmental performance throughout product lifecycles, concentrating efforts on eco-friendly equipment development and dissemination, while researchers must acknowledge scientific responsibility in selecting sustainable alternatives. Through such integrated approaches, wet-laboratories can simultaneously reduce environmental burdens while enhancing research reliability and operational efficiency.

[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [19] [52] [53] [54] [55] [56] [35] [52] [23] [57] [58] [59] [60] [61] [62] [52] [36] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74] [75]

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Author Contributions and AI Usage

[Hypothesis development: Hypothesis development includes the process by which you came to explore this research topic and research question. This can involve the background research performed by either researchers or by AI. This can also involve whether the idea was proposed by researchers or by AI.
Answer: Liner AI-led (80%), Human review and validation (20%)
Explanation: The research team presented questions about problems we identified to AI, and AI formulated and proposed core research hypotheses and research questions. Based on these proposals, we received responses from AI, which the research team then reviewed and validated.

2. Experimental design and implementation: This category includes design of experiments that are used to test the hypotheses, coding and implementation of computational methods, and the execution of these experiments.
Answer: Liner AI-led (80%), Human supervision and validation (20%)
Explanation:Experimental design was conducted by Liner AI, and coding and implementation were performed by Claude AI. The research team reviewed the design and code proposed by AI to identify deficiencies or errors, then proceeded with modifications and improvements through additional questions and responses.

3. Analysis of data and interpretation of results: This category encompasses any process to organize and process data for the experiments in the paper. It also includes interpretations of the results of the study.
Answer: Liner AI-led (85%), Human validation (15%)
Explanation: Data collection, organization, and statistical analysis were performed by AI, and visual graph generation and primary result interpretation were also produced through AI. The research team reviewed the validity of AI-generated analysis results and interpretations and provided final approval.

4. Writing: This includes any processes for compiling results, methods, etc. into the final paper form. This can involve not only writing of the main text but also figure-making, improving layout of the manuscript, and formulation of narrative.
Answer: Liner AI-led (90%), Human editing and review (10%)
Explanation: The majority of paper writing, including initial drafting, editing, and figure creation, was handled by AI. The research team played the role of reviewing AI-generated content and modifying and supplementing it to align with research objectives.

5. Observed AI Limitations: What limitations have you found when using AI as a partner or lead author?
Description:

- **Repetitive response issues**: Frequent cases where AI provided identical responses even when specific modification suggestions were presented
- **Inappropriate citations**: Problems with indiscriminate citation of papers or materials unrelated to the research topic (e.g., citing irrelevant papers when our topic was environmental-focused)
- **Limited contextual understanding**: Tendency to provide generic responses without sufficiently understanding the overall context of the research