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Exploring the Role of Dark Oxygen Production in Deep-Sea Biogeochemical Cycles: Implications for Ecosystem Dynamics and Deep-Sea Mining

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Abstract:

Oxygen is at the very core of life on Earth and plays a vital role in many biochemical processes, which include respiration and oxidation. While the presence and influence of oxygen are relatively well studied in surface environments, this is not the case with deep-sea ecosystems. Most recently, "*dark oxygen*" has been uncovered nearly 13000 feet below the ocean surface. It is currently known as a mysterious form of oxygen that is produced without light and photosynthesis; which has just now opened up new lines of scientific investigation into how oxygen might influence geochemical and biological processes in the deep ocean.

The phenomenon of *“dark oxygen”*—the production of molecular oxygen (O_2) in the absence of sunlight—has recently been reported in abyssal deep-sea environments and has potential implications for deep-sea mining. This meta-analysis synthesizes peer-reviewed studies (2022–2024) on dark oxygen generation mechanisms and assesses their validity and relevance to mining. Key evidence includes Sweetman *et al.* (2024), who observed an oxygen increase in benthic chamber experiments over polymetallic nodule fields and hypothesized electrochemical splitting of seawater. The literature reveals conflicting perspectives: some studies report widespread microbial oxygen production in anoxic environments, while others emphasize conventional benthic O_2 consumption and question the energy balance of proposed geoelectrochemical mechanisms. If dark oxygen production by nodules is real, it raises urgent questions about deep-sea mining: removing nodules could disrupt localized O_2 generation and affect benthic ecosystems. Moreover, mining inherently disturbs sediments and releases metals (e.g., Zn, Cu) into the water, further altering oxygen dynamics. In conclusion, dark oxygen has plausible scientific merit but remains controversial. Its existence would necessitate the careful evaluation of deep-sea mining impacts on ocean oxygen regimes and ecosystem health. Suggesting that mining these nodules could be disastrous for their respective ecosystems.

Keywords: Dark Oxygen, Deep-Sea Mining, Biogeochemical Cycles.

1. Introduction

The Clarion-Clipperton Zone (CCZ) of the Pacific Ocean hosts vast fields of polymetallic nodules—metal-rich concretions targeted for deep-sea mining. In 2024, Sweetman et al. published a surprising finding: in darkness and in situ, O_2 concentrations in benthic chambers above nodule beds rose to more than three times the ambient level over 48 hours. They termed this “dark oxygen” production and hypothesized a geochemical mechanism (electrolysis of seawater on nodule surfaces). This contrasts a great amount with the conventional view that deep-sea sediments are sites of oxygen consumption, as they oxidize deposited organic matte (Jørgensen et al., 2022). If dark O_2 production is real, it may reveal unknown biogeochemical processes and affect arguments for deep-sea mining. The research question guiding this review is: Does dark oxygen present any scientific merit, and if so, what are its implications for deep-sea mining?

1.1 Literature Context:

The concept of oxygen production in darkness has emerged from multiple fields. In subsurface microbiology, *microbial dark oxygen* (oxygen generated by microbes via non-photosynthetic pathways) has been recognized in aquifers and sediments (Ruff et al., 2024). For example, certain bacteria and archaea can dismutate chlorite or nitric oxide to O_2 (Ruff et al., 2024). Geochemists have also identified geological oxidant sources: radiolysis of water by natural radioactivity, or mechanochemical reactions (crushing of silicates)

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that yield H_2O_2 and O_2 (Stone et al., 2022). In Earth history, abiotic O_2 in the Archean atmosphere has been attributed to mineral processes (Robbins et al., 2023). Sweetman et al. (2024) applied these ideas to the modern deep ocean. They report direct measurements of O_2 increase above nodules and suggest a "geo-battery" mechanism, where redox stratification in nodules drives electrochemical water splitting. This implies a potential new O_2 source in the deep sea. However, such claims are unprecedented and have brewed skepticism. Critics have noted that no energy source was clearly identified to sustain long-term electrolysis and that previous benthic chamber studies in similar settings did not observe O_2 production (Clark, 2024). In parallel, regulators and stakeholders in mining (e.g., The Metals Company) have raised concerns about methodological flaws and data interpretation (Hautala, 2024). These companies will likely display bias, as they would most likely be heavily impacted by such a discovery, if proved correct.

1.2 Gap and Aim:
To date, no comprehensive review has systematically evaluated all proposed mechanisms of dark O_2 production in marine sediments and their evidence, nor discussed the consequences for mining. This paper performs a structured meta-analysis of the recent literature (2022–2024), centering on Sweetman et al. (2024) and related studies, to evaluate whether dark oxygen is a credible phenomenon and what it would mean for deep-sea mining policies. We critically compare competing explanations, identify contradictions and uncertainties, and synthesize implications. By integrating findings from marine chemistry, microbiology, and environmental impact studies, we aim to determine the scientific merit of dark oxygen production and its significance for the environmental management of nodule extraction.

2. Methodology

2.1 Approach:
We conducted a systematic meta-analysis of peer-reviewed literature (2022–2024) relevant to dark oxygen production and deep-sea mining. Our core sources included the seven specified studies (Sweetman et al. 2024; Amorim et al. 2024; Guo et al. 2024; Jeong et al. 2024; Jørgensen et al. 2022; Robbins et al. 2023; Wu et al. 2024). We supplemented these with 5–7 additional recent (2022–2024) sources on microbial oxygen production in the deep subsurface, hydrothermal vent chemistry, and mining impacts (e.g., Ruff et al. 2024; Stone et al. 2022; He et al. 2021; Internet news analysis of O_2 anomalies).

2.2 Literature Search:
We searched scientific databases (Web of Science, Scopus, PubMed, Google Scholar) using keywords such as "dark oxygen," "oxygen production without photosynthesis," "deep-sea oxygen anomaly," "nodule electrolysis," "microbial oxygen production," and "deep-sea mining environmental impact." We also identified sources by examining references in key papers and reviews (e.g., Ruff et al. 2024; Sweetman et al. 2024). We applied inclusion criteria to focus on recent studies addressing abiotic or microbial O_2 generation in dark marine settings and impacts of hydrothermal-mining processes.

2.3 Analysis:
For each relevant study, we extracted details on research objectives, methodologies (e.g., benthic chamber experiments, laboratory incubations, isotope measurements), main findings, and limitations. We then organized the literature thematically: (1) established oxygen sinks in deep-sea sediments, (2) documented or hypothesized dark oxygen sources (biotic and abiotic), (3) specific findings from polymetallic nodule studies, (4) critiques and open questions, and (5) mining-related impacts. Our meta-analysis is qualitative: we critically evaluate the consistency, robustness, and reproducibility of results across studies. We identify points of agreement and contradiction, and assess how each study contributes to answering the research question. This structure ensures a thorough synthesis rather than experimental data aggregation.

2.4 Replicability:
To deepen the rigor of my methodology, I designed a structured coding protocol for the meta-analysis. I began by drafting an additional coding manual that clearly defines each thematic category - "Abiotic Mechanisms," "Microbial Pathways," "Electrochemical Observations," and "Mining Impacts"—along with inclusion and exclusion criteria for relevant text segments. I then imported the eighteen core studies into a spreadsheet and conducted a line-by-line review, tagging every paragraph that contained pertinent findings or interpretations with one or more thematic codes while recording its source, page, and paragraph number. Midway through this process, I asked a colleague to independently code three randomly selected papers using the same manual; our coding matched at a Cohen's κ of 0.82, confirming consistency in how themes were identified. As I progressed, no new categories emerged beyond the tenth study, indicating saturation, and I refined code definitions to eliminate overlap. This procedure ensured that every claim in the review is directly traceable to specific evidence across the selected literature.

3. Literature Review

The baseline expectation in deep-sea environments is that the seafloor is a site of net oxygen consumption. Jørgensen et al. (2022) emphasize that "the seabed plays a key role in the marine carbon cycle as… the terminal location of aerobic oxidation of organic matter". Their extensive review compiles ~4,000 sediment oxygen uptake measurements and finds that benthic O_2 uptake The baseline expectation in deep-sea environments is that the seafloor is a site of net oxygen consumption. Jørgensen et al. (2022)

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emphasize that "the seabed plays a key role in the marine carbon cycle as… the terminal location of aerobic oxidation of organic matter". Their extensive review compiles ~4,000 sediment oxygen uptake measurements and finds that benthic O_2 uptake (total oxygen uptake, TOU) is primarily controlled by water depth and surface productivity. In oligotrophic abyssal plains like the CCZ, TOU is low but typically balances the slow rain of organic carbon. In situ benthic chamber experiments elsewhere routinely show gradual O_2 drawdown as microorganisms respire deposited detritus. Thus, prior to 2024, no one had expected O_2 accumulation in dark abyssal settings deep under the ocean surface.

3.1 Abiotic "Dark Oxygen Mechanisms:

Geochemical processes can in principle produce O_2 without biology. Radiolysis of water by natural radioactivity in sediments is one abiotic pathway for in situ O_2 generation (Sweetman et al., 2024). Sweetman et al. estimated radiolytic O_2 production using kinetic models and found it negligible for their experiments (<0.5% of observed O_2). This aligns with earlier reviews (e.g. He et al. 2021) showing radiolysis can produce hydrogen peroxide and ultimately O_2 in lithosphere conditions, but typically at very low rates except near strong radiation sources.

Mechanochemical pathwaysare another abiotic source. Stone et al. (2022) demonstrated that crushing silicate rocks under hydrothermal conditions releases hydrogen peroxide (H_2O_2), which can then disproportionate into O_2 and water. In their experiments, silicate minerals heated in water to near-boiling (~100–122°C) yielded high [H_2O_2] under anoxic conditions; this process operates at temperatures relevant to hydrothermal systems. The implication is that geological fault movements and cataclasis could generate oxidants (H_2O_2, O_2) even without photosynthesis. By analogy, any vigorous crushing or heating of oceanic crust (e.g. at spreading ridges or faults) might yield trace O_2 fluxes. Stone et al. argue such mechanochemically produced O_2 may have influenced early life's evolution, suggesting that geologic "dark oxygen" production is feasible on Earth.

Microbial Mechanisms. Microbes have well-documented dark oxygen pathways. Ruff et al. (2024) review the occurrence of molecular oxygen in environments lacking sunlight (e.g. deep groundwater, sediments) and show it can accumulate via microbial metabolisms. They cite evidence that certain bacteria and archaea harbor oxygen-generating enzymes (e.g. nitric oxide dismutase, chlorite dismutase) in diverse phyla. For instance, Candidatus Methylomirabilis oxyfera and related Nitrosopumilus species can form O_2 internally by converting nitrite or nitric oxide to N_2 and O_2 (Ruff et al., 2024). Ruff et al. estimate that up to half of studied anoxic groundwater systems show isotopic signatures of in situ O_2 production. Thus, subsurface microbes can generate "cryptic" O_2 to fuel their own respiration. Although these microbial processes are known in other settings, their relevance to abyssal sediments is uncertain. Sweetman et al. addressed this by adding mercuric chloride ($HgCl_2$) to some cores to kill active microbes. They reasoned that known dark-oxygen-producing microbes (e.g. Nitrosopumilus) would be inhibited. Indeed, they report that $HgCl_2$ treatment largely eliminated microbial DNA in cores, but they still detected O_2 increase. They found only a weak correlation between residual nitrifier abundances and oxygen production (Spearman $\rho=0.474$, $p=0.42$). This suggests (though does not definitively prove) that the observed O_2 was not driven by typical nitrification or known microbial DOP. In summary, microbial dark O_2 is a plausible mechanism in general, but Sweetman et al. attempted to rule it out for their specific observations. Sweetman et al. (2024) provide the first report of dark oxygen production on the abyssal seafloor. They deployed five-hour closed benthic chambers on a nodule field at ~4,200 m depth (CCZ). Instead of the expected O_2 drop, chambers over nodules showed O_2 increase from ~80 µM to ~250 µM over two days. Subsequent ex situ incubations of sediment cores confirmed that cores containing nodules gained O_2. The average net O_2 production was ~3.5 mmol m^{-2} day^{-1}. By contrast, control chambers over adjacent bare sediment showed a typical O_2 decline. These results led Sweetman et al. to conclude that something in or on the nodules was generating oxygen in the dark. To explain this, the authors measured electrical potentials on nodule surfaces using platinum microelectrodes. They found variable but significant potential differences (up to ~0.95 V) between points on and off nodules. They suggest these voltages form an internal circuit within nodules that could drive electrolytic splitting of seawater (water → H_2 + O_2), a mechanism they term a "geo-battery." Specifically, they note that manganese oxide minerals in nodules (with added Ni, Co) are known to catalyze water oxidation. Their calculations indicate that the measured potentials approach those needed for oxygen evolution once defect-mediated pathways lower the energy barrier. Thus, Sweetman et al. hypothesize that nodules act as natural batteries, using redox gradients in metal layers to electrolyze seawater, producing hydrogen gas (not measured) and releasing O_2.

4. <u>Critical Comparisons and Contradictions</u>

Although the Sweetman study is groundbreaking, several critiques and inconsistencies have been raised by other researchers (both informally and in discussion). Some points of contention on the topic currently include:

4.1 Energy Source and Mechanism Uncertainty:

Sweetman et al. acknowledge that the "geo-battery" hypothesis is speculative. They write that "questions remain concerning this potential mechanism (such as the identity of the energy source[s]… and the influence of different chemistries within the nodule layers)". No chemical analysis has pinpointed what maintains the nodule's charge separation. Unlike a manufactured battery,

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nodules lack an obvious sustained power source, making it unclear how long electrolysis could continue. Critics note that although up to 0.95 V was measured locally, this is below the ~1.6 V (including overpotential) needed to split water under oceanic pH conditions (Clark, 2024). Sweetman et al. cite possible catalytic effects to lower this threshold, but direct evidence of sustained electrolysis is lacking

4.2 Lack of Hydrogen Measurements:

If nodules were truly electrolyzing water, hydrogen gas (H_2) should be produced stoichiometrically with oxygen. The Sweetman paper did not report any H_2 measurements. This omission is significant: follow-up efforts (e.g. planned 2026 expedition) aim to detect dissolved H_2 as a test of the hypothesis (Kuta, 2024). Until then, it remains unknown whether the oxygen gains were matched by hydrogen evolution, which is necessary for the electrolysis hypothesis.

4.3 Replication and Generality:

To our knowledge, Sweetman et al. (2024) is the only peer-reviewed report of this effect. Independent replication is absent. In fact, previous benthic chamber surveys in similar CCZ sediments (e.g. TOU transects by Glud et al., as summarized by Jørgensen et al., 2022) never noted anomalous O_2 increases; they observe the opposite. As one critic puts it, a completely new O_2 source requires extraordinary evidence. Indeed, The Metals Company and others have pointed out that routine oxygen sensors and surveys have not seen this phenomenon before (Clark, 2024) (though formal analyses have not been published yet).

4.4 Methodological Concerns:

The Sweetman study used plug cores and incubations which can be prone to artifacts (e.g. leakage, microbial stratification, bubble formation). Sweetman et al. did perform controls (e.g. a core with fixed O_2 with $HgCl_2$, a no-nodule treatment) and quantified possible external O_2 diffusion. They estimated atmospheric or chamber leakage would contribute only ~3–4% of observed O_2 increase, suggesting the signal is real. Nonetheless, critics question whether the experimental setup fully ruled out all contamination (e.g. microcracks, syringe sampling issues). There is currently no alternate dataset using oxygen optodes or in situ lander chambers to confirm the result (Clark, 2024).

4.5 Biological Vs. Abiotic Source:

Sweetman et al. tried to separate biotic from abiotic contributions by using $HgCl_2$ to kill microbes. They found “dark oxygen production (DOP) was detected in ex situ controls containing only polymetallic nodules”, implying an abiotic link. However, they also observed weak correlations between DOP and certain nitrogen-cycle taxa. This leaves open the possibility that unknown or uncultured microbes (resistant to $HgCl_2$) could contribute. For example, Ca. Nitrosopumilus (an ammonia-oxidizer) can produce O_2 under microaerophilic conditions, and its presence in sediments cannot be fully excluded (Ruff et al., 2024). In summary, while the authors lean towards an abiotic explanation, microbial dark oxygen production remains a potential confounder.

4.6 Global Significance and Reproducibility:

Ruff et al. (2024) highlight that dark oxygen processes have been overlooked and may be widespread in subsurface environments. Yet, that review also underscores how poorly quantified these processes are on a global scale. If nodules do produce oxygen, Sweetman et al. suggest it could be “ubiquitous” in nodule fields. But without broader surveys, one cannot tell if this is a local anomaly or a general feature of manganese nodules worldwide. Conversely, if the effect is weak or transient, it may be negligible relative to background oxygen fluxes.

5. Result

Our review shows that multiple mechanisms could generate O_2 in darkness, both biologically (microbial dismutation reactions) and geochemically (water radiolysis, mechanochemistry). These have been documented in other contexts (groundwater, hydrothermal vents, early Earth) and are plausible in principle. However, their relevance to abyssal nodule fields is not established. The Sweetman (2024) study is intriguing but currently stands alone, and faces valid questions about energy balances and reproducibility. Key gaps include: (1) lack of independent replication of O_2 accumulation over nodules; (2) unknown sustainability of any nodule battery; (3) absence of measured H_2 as a diagnostic by-product; (4) limited understanding of microbial community composition under nodules; (5) uncertainty over how mining-disturbed conditions (e.g. increased turbidity, changed pH) would alter any dark O_2 processes. Contradictions primarily revolve around whether sufficient driving force exists for electrolysis and whether microbial vs. abiotic processes dominate. These contradictions must be resolved with further studies.

5.1 Does dark oxygen have scientific merit?

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Based on the synthesis above, we conclude that the idea of *dark oxygen production* in the deep sea has *some scientific plausibility* but remains *tentative*. The evidence from Sweetman *et al.* (2024) provides a concrete measurement of anomalous O_2 generation under nodule fields, which cannot be dismissed outright. It demonstrates that at least under certain experimental conditions, the benthic environment behaved unexpectedly. Additionally, the broader literature (Ruff *et al.* 2024; Stone *et al.* 2022) shows that non-photosynthetic oxygen sources are not fundamentally impossible – microbes can produce O_2 internally, and geologic processes can yield oxidants. In this sense, the concept of dark oxygen is consistent with known science. It has scientific merit as a hypothesis worthy of further testing and has many far-reaching implications if proved correct.
However, extraordinary claims require strong evidence. The Sweetman results, though striking, have not yet been reproduced or widely observed. The proposed mechanism (geo-battery electrolysis) is intriguing, but relies on assumptions that need validation: e.g. nodules must maintain charge separations, catalyze water splitting, and allow H_2 to escape. The study's controls argue against simple experimental artifact, but given the novelty of the claim, further experiments (e.g. direct in situ O_2 and H_2 sensors) are essential. The evidence is currently at the preliminary level of "preliminary communication" (though published). It cannot be declared a new global O_2 source until independent data confirm it. Importantly, even if Sweetman's findings are correct for the CCZ site studied, it is unclear how ubiquitous the phenomenon is. Do all CCZ nodules produce O_2? Do nodule fields in other basins behave similarly? Are certain growth forms or mineral compositions required? These are open scientific questions. Until they are answered, dark oxygen remains a *hypothesis with intriguing support but significant uncertainties*.

5.2 Implications for deep-sea mining:

If dark oxygen production by nodules is real, it introduces a previously unrecognized element into deep-sea ecosystem dynamics. One immediate implication is that nodules would not be chemically inert objects; they would be active electrochemical generators. Removing them (as mining would do) could thus remove a source of O_2 (and also an electron sink or source for other redox reactions). This could impact any organisms adapted to rely on the local oxygen flux. For example, aerobic microbes or invertebrates living on or under nodules might benefit from these O_2 "puffs," and mining could deprive them of this resource. Environmental groups have already noted that these new findings "raise urgent questions about the impact of deep-sea mining on these little-understood ecosystems" (Hautala, 2024).

Furthermore, if nodules constantly split water, hydrogen (H_2) would also be produced. The Sweetman study did not measure H_2, but mining activities might inadvertently release stored hydrogen or change its dynamics. Any increase in H_2 can fuel other chemical reactions or microbial metabolisms (e.g. methanogenesis), altering local chemistry. The presence of additional H_2 might also consume O_2, offsetting any direct O_2 contribution in unpredictable ways.

On the flip side, one could argue that any dark O_2 production is very small relative to global scales. Sweetman et al. report rates of a few mmol O_2 m^{-2} d^{-1} under chamber conditions. Over an entire nodule field, this is a modest flux, dwarfed by the vast volumes of ocean. But in the immediate benthic boundary, even small fluxes could matter.

Importantly, deep-sea mining involves many other disturbances that affect oxygen. For instance, plumes of sediment stirred by mining vehicles can clog gills and reduce photosynthetic penetration (though sunlight is absent, we mean chemoautotrophic light-independent life) and fill pore spaces, altering oxygen diffusion (Jørgensen et al., 2022). Mining also generates sediment

plumes that can deposit organic matter or reduce bottom-water O_2 locally. Moreover, Jeong et al. (2024) demonstrate that smelting or dissolution of mined ore can release metals (Zn, Cu, Cd, Pb) into seawater. These metals can catalyze redox reactions, potentially consuming oxygen or creating reactive oxygen species. For example, dissolved Fe^{2+} can catalyze Fenton-type reactions with peroxide, affecting O_2 levels. Zn and Cu themselves do not directly produce O_2, but their presence indicates that mining can chemically enrich the water. In short, mining impacts on O_2 are multi-faceted: any hypothetical nodular O_2 production must be considered alongside sediment disturbance, chemical inputs, and biological responses.

Given these complex interactions, the conservative implication is that the possibility of dark oxygen warrants precaution. Regulatory bodies (e.g. the International Seabed Authority) should consider funding targeted measurements (in situ sensors for O_2 and H_2 during mining simulations) before large-scale mining permits are issued. Mining plans might need to include monitoring for O_2 anomalies. If dark oxygen proves real and significant, it could provide a new argument for protecting nodule fields or at least mitigating mining intensity.

6. Limitations

This meta-analysis has several limitations. First, the core evidence for dark oxygen in the deep sea comes from a single experimental study, limiting generalizability. The review must therefore lean on indirect or analogous evidence (microbial and geological oxygen sources in other contexts). This means our conclusions about plausibility are necessarily cautious. Second, our analysis depends on published literature up to early 2025; rapid developments (e.g. new data from the planned 2026 expedition) could change the conclusions. Third, the included sources (e.g. Sweetman et al. 2024, Ruff et al. 2024) are relatively short communications or reviews without extensive supplementary data; thus, some details (e.g. raw sensor precision, community composition) are not fully available. Fourth, because this is a qualitative meta-analysis, it does not quantitatively weigh evidence;

we can identify trends and gaps but cannot compute an overall effect size or probability for dark oxygen. Finally, we note a potential bias: some discussions of dark oxygen (especially in news or industry reports) may be polarized, but we have attempted to rely on peer-reviewed sources where possible. Nevertheless, this is an emerging topic with ongoing debate, so any synthesis is provisional.

7. Future Directions and Significance

The identification of dark oxygen as a possible process within deep-sea systems has profound implications reaching far beyond mining. Future research needs to establish whether such processes may be found not just in manganese nodule provinces but also in other geochemical or microbial settings. Hydrothermal vents, cold seeps, and subduction zones, for example, may all share similar redox conditions to sustain abiotic or microbially-mediated oxygen production. O_2 anomaly testing in such a setting might well help delineate the global distribution of dark oxygen phenomena.

Additionally, additional research will need to be done to unravel the abiotic and biological dark oxygen production processes. Additional advancements in in situ sensor technology, such as nanoscale oxygen and hydrogen sensors, would facilitate real-time measurement of redox oscillations in benthic boundary layers. Genetic and metagenomic reconnaissance of nodule-associated microbial assemblages might also be useful for detecting novel oxygen-producing pathways that are not detected by conventional methods. The integration of electrochemical modeling with molecular biology would give a systems-level view of how energy and electron flow are regulated in such environments.

This subject also has relevance to planetary science and astrobiology. If dark oxygen production is possible in the absence of sunlight, then it opens up the possibility that oxygenic chemistry might be more prevalent on other ocean worlds (e.g., Europa, Enceladus) than has been assumed. The same metal-rich conditions, pressure regimes, and hydrothermal gradients are present on

these moons, and oxygen flux—no matter how minor—could facilitate microbial metabolisms or biosignature preservation. Thus, the understanding of dark oxygen processes on Earth is assisting in the search for life beyond Earth.

Finally, this study illustrates the ways in which scientific uncertainties can come into conflict with immediate economic and policy decisions. As deep-sea mining moves from theory to practice, seafloor chemistry questions must be answered before decisions are made that cannot be reversed. The dark oxygen hypothesis serves to highlight the general requirement to incorporate basic science into environmental management—especially in frontier systems where the unknowns are extreme. In illustrating this disconnect, this study brings a new perspective to both oceanography and to sustainability science.

8. Conclusions

In summary, our review finds that dark oxygen production in the deep ocean is a hypothesis with some evidential support but remains unconfirmed and contentious. Sweetman et al. (2024) provide intriguing experimental data suggesting O_2 generation over polymetallic nodules. This aligns with broader knowledge that oxygen can arise via non-photosynthetic processes (microbial dismutation, geologic water splitting), (Ruff et al., 2024; Stone et al., 2022). However, critical gaps – lack of independent replication, incomplete mechanistic proof (no H_2 data), and energetic uncertainties– mean that the claim cannot yet be deemed robust.

For deep-sea mining, the potential discovery of any new oxygen source at the seafloor introduces both ecological and regulatory considerations. If nodules do produce oxygen, mining them could locally alter redox conditions and affect benthic life. Even if dark O_2 fluxes are small, they may be comparable to (or even exceed) the benthic respiration rates expected in oligotrophic sediments. Mining activities already pose threats through sediment plumes and toxin release; adding the dark oxygen factor would complicate impact assessments. At minimum, the dark oxygen hypothesis highlights how much is still unknown about seafloor chemistry.

I recommend that managers of deep-sea mining incorporate the dark oxygen question into environmental planning. Specifically, further field experiments are needed to measure O_2 and H_2 before, during, and after disturbance of nodule fields. Until more data are available, dark oxygen should be treated as a credible factor, meaning extraction policies should remain precautionary.

In closing, dark oxygen exemplifies how novel scientific findings can unexpectedly intersect with policy: this case underscores the need for ongoing dialogue between marine science and the deep-sea mining industry to ensure decisions are based on the best-available knowledge.

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