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Continued cathodic operation in coral restoration: Are calcification benefits generalizable?

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ABSTRACT

Electrochemically induced mineral accretion has been proposed as a way to support coral transplantation and accelerate coral growth. At a submerged cathode, reduction reactions raise local pH and can produce a mineral coating, but the same system changes substrate condition, corrosion, attachment, and seawater chemistry. This review asks whether keeping a mineral-coated cathodic structure connected to external power ("continued externally powered cathodic operation") improves scleractinian coral calcification or skeletal growth beyond coating effects. Experimental reports are classified by the biological outcome, measured and weighted by comparator directness and treatment-level replication. Quantitative pooling was inappropriate because outcomes, exposure conditions, experimental units, and controls were incompatible. The strongest direct calcification experiment reported a 43% increase for 5-mm *Pseudodiploria clivosa* microfragments within a measured elevated-pH boundary layer, but no significant benefit for 15-mm conspecifics or for 50-mm *Acropora cervicornis*. The closest field comparison of continued power with power removal after coating found no consistent scleractinian geometric-growth advantage and reported adverse bleaching or tissue outcomes in some taxa during a heatwave. Other field studies produced positive, null, or negative extension and planar-growth results, but most did not isolate continued power from substrate, attachment, corrosion protection, structure or site, and several failed to replicate at the powered-structure level. The evidence therefore supports a conditional local mechanism, not a general restoration benefit: continued cathodic operation can enhance coral-produced calcification when living tissue remains within a favorable electrochemical boundary layer, but current experiments do not establish that keeping mineral-accreted field structures powered generally adds a skeletal-growth benefit. Generalization is limited principally by fragment height relative to the boundary layer, flow, exposure duration, taxonomic and morphological coverage, non-equivalent controls, indirect growth proxies and insufficient treatment-level replication.

Keywords: scleractinian coral; calcification; skeletal growth; seawater electrolysis; mineral accretion; cathode; causal inference; coral restoration

1. INTRODUCTION

Active coral restoration increasingly uses coral propagation, transplantation, and artificial substrates, but a method that secures fragments or produces a reef-like structure does not necessarily accelerate coral skeletal production or restore ecosystem function (Boström-Einarsson et al., 2020). Electrochemically induced mineral accretion is unusual because it combines at least two possible interventions: creation of a mineral-coated artificial substrate and continued modification of seawater chemistry near a powered cathode. Claims about "coral growth" can therefore refer to several different processes that demand different types of evidence.

At a cathode in seawater, water reduction can be represented in simplified form as:

$$2H2O + 2e- \rightarrow H2 + 2OH-.$$

The production of hydroxide raises pH levels close to the cathode, shifts dissolved inorganic carbon toward carbonate ions, and can promote calcium carbonate precipitation. In sufficiently alkaline conditions, magnesium hydroxide can also precipitate, but these external deposits are not coral skeleton. A coral produces its aragonitic skeleton through a biologically regulated extracellular calcifying medium beneath its tissue, so an increase in mineral mass on the cathode, a longer branch, a larger two-dimensional silhouette, and a greater mass of coral-produced CaCO3 are related but non-equivalent outcomes (Tambutté et al., 2011). Anodic reactions also require attention because acidity and oxidants, including reactive types of chlorine in some designs, may be produced at a distance from the cathode (Lees et al., 2024; Kiel et al., 2026).

This distinction creates a measurement problem. Linear extension can increase while skeletal density or total mass does not increase proportionally. Planar area measurement can record living tissue spread, colony geometry or partial mortality rather than the amount of skeleton deposited (Samidon et al., 2022). Established calcification methods also estimate different quantities: buoyant weight and alkalinity-anomaly measurements generally estimate net calcification, whereas isotope incorporation can target shorter-term gross calcification but introduces its own assumptions (Cohen et al., 2017; Gómez Batista et al., 2020). On a powered cathode, external CaCO3 and Mg(OH)2 precipitation can contaminate apparent mass change if it is not measured and removed analytically or physically (Kiel et al., 2026). A study may define any of these variables as "growth", but this term cannot automatically be interpreted as increased coral calcification.

There is also a causal-control problem. A powered steel structure can acquire a mineral coating and avoid corrosion, whereas an unpowered steel control may remain bare and corrode. Corals may be attached using different methods, positioned at different heights, or placed at different sites. A comparison between these structures estimates the combined effect of this treatment package, not necessarily the incremental effect of continued cathodic operation. The most useful test for that incremental effect would begin with equivalent mineral-accreted structures and then continue power on a randomly assigned, independently replicated subset while disconnecting the rest.

A recent scoping review mapped 32 publications on mineral accretion technology across marine benthic organisms and found pervasive weaknesses in controls and reporting (Rivas-Mena et al., 2026). The present review asks a narrower question that the broader map was not designed to answer. It restricts the biological population to living scleractinian corals, separates coral-produced calcification from skeletal-growth proxies, reconstructs overlapping experimental datasets, and weights evidence according to whether its comparator identifies an incremental effect of continued operation.

The review question is:

How strong is the evidence that continued externally powered cathodic operation improves scleractinian coral calcification and skeletal growth above and beyond mineral-accreted substrate effects, and what limits the generalizability of reported benefits?

The primary purpose is to determine whether a reproducible incremental biological effect is supported. Outcome measurement and control design are used as evidence-weighting tools: they determine how convincingly each experiment can answer that causal question. The review then asks whether any supported benefit can be generalized across coral forms, hydrodynamic conditions, exposure periods, and field settings. It does not decide whether every electrochemical restoration system "works."

2. METHODS

2.1 Review approach

This study used a targeted critical-review design. The evidence set was assembled from scholarly-search and publisher records, the project's verified source inventory, and comparison with the studies included by Rivas-Mena et al. (2026). Reference lists and cited-by records were checked selectively to locate related experiments; this was not a comprehensive citation-tracing protocol. Literature available through 3 August 2026 was considered. The synthesis focused on causal relevance to the review question rather than counting positive and negative reports equally.

For transparency, Table A1 summarizes the study-selection information that can be reconstructed from the review record; because this was a targeted critical review, the initial search yield and formal screening counts were not prospectively recorded.

Table A1. Search summary for the targeted critical review.

Study-selection stage	Number / status
Initial search yield and formal screening	Not prospectively recorded

Full-text reports retained in the core evidence base	9
Additional records discussed outside the core methods-level synthesis	3
Principal experimental datasets after consolidation of overlapping reports	8

A quantitative meta-analysis was not attempted because the studies differed fundamentally in taxa, current density, duration, treatment unit, comparator and outcome measurement. Directional vote counting was also avoided because a weakly controlled positive result and a directly controlled null result do not provide equivalent evidence about continued cathodic operation.

2.2 Eligibility

Core evidence comprised controlled laboratory or field experiments in which living scleractinian corals were exposed to continued externally powered cathodic operation. Eligible primary outcomes were explicitly measured calcification or skeletal mass change, linear skeletal extension, planar skeletal growth, skeletal area or volume, density and budding or formation of new skeletal units. Survival, bleaching, live-tissue condition, photophysiology, settlement, recruitment and attachment were retained only as separate safety or interpretive outcomes.

Galvanic-only systems, studies without living corals, artificial-reef observations without a causal comparator, proprietary claims without methods and outcomes that could not be separated for scleractinians were excluded from the primary effect synthesis. Mechanistic models, chemistry-only experiments and non-electrochemical alkalinity-enhancement studies were used for interpretation, not treated as proof of a biological effect from continued cathodic operation. Where multiple publications reported the same experiment, they were treated as one dataset rather than independent replications.

For example, the Okinawa study by Kihara et al. (2013) was retained as contextual evidence about settlement, current density and mineral-coated substrates but excluded from the primary effect synthesis because its principal experimental system was galvanic rather than continuously externally powered.

2.3 Extraction and outcome classification

For each report, the following information was extracted where available: species, setting, duration, fragment size, cathode and anode design, voltage, current or current density, power schedule, comparator, treatment-assignment level, number of independent structures or aquaria, biological measurement, attrition, effect direction and magnitude, statistical result and disclosed limitations.

Outcomes were reclassified from the actual method rather than accepted under the authors' general label of "growth":

coral skeletal $CaCO_3$ mass or explicit calcification;

linear extension;

planar area or tissue spread;

estimated colony volume;

budding or corallite production; and

secondary survival, tissue, bleaching, physiological, settlement, or recruitment outcomes.

External mineral deposition was recorded separately. A mass-based outcome was considered vulnerable to contamination when cathodic precipitate could not be distinguished from skeleton produced by the coral.

2.4 Causal-control appraisal

Control designs were interpreted according to the contrast they could identify. Highest directness was assigned to equivalent pre-coated structures for which continued power was compared with power removal. A powered-versus-unpowered matched-metal comparison could test a treatment package but might combine electricity with coating and corrosion protection. Comparisons using different materials, attachment methods, heights, structures or sites received lower directness.

Replication was assessed at the level of treatment assignment. If one whole structure received power, coral fragments on that structure were subsamples, not independent replicates of the electrical treatment. Treating those fragments as independent electrical replicates is pseudoreplication because the treatment itself was not independently repeated (Hurlbert, 1984). Appraisal also considered current reporting, baseline equivalence, missing fragments, survivor-only analysis, duration, outcome validity, and whether overlapping reports were counted only once.

2.5 Synthesis

Evidence was synthesized around the primary causal question, with outcome validity, comparator directness and treatment-level replication used to determine evidentiary weight. Tropical and cold-water experiments were not assumed to be interchangeable. Current density, duration, species, morphology, fragment height, and water flow were evaluated only when a study directly measured them or when a pattern was supported across studies. A qualitative sensitivity analysis then asked whether the conclusion changed when attention was restricted to (i) direct calcification measurements and (ii) experiments closest to an equivalent pre-coated power-on versus power-off contrast. The final conclusion was based on the inference that survived those restrictions.

3. RESULTS

3.1 Evidence-base characteristics

The accessible complete core texts comprised the 2004 follow-up from the Philippine program reported by Sabater and Yap (2002, 2004); the Indonesian *Acropora* program reported by Borell et al. (2010) and Romatzki (2014); a cold-water laboratory experiment by Strömberg et al. (2010); and later field or laboratory studies by Chavanich et al. (2013), Samidon et al. (2022), Cook et al. (2023), Knoester et al. (2024), and Kiel et al. (2026). The 2002 Sabater and Yap record was bibliographically verified but its full text was unavailable; it was used only to recognize continuity with the accessible 2004 report, not for methods-level extraction. The Borell experiment is also Experiment 2 within the wider Romatzki program and was counted once when judging replication.

The studies ranged from 60-day laboratory exposures to field monitoring of approximately one year or longer. They included branching, massive and cold-water scleractinians. Electrical exposure ranged from tens of milliamperes per square metre in low-current studies to several amperes per square metre in other trials, but current density at the coral surface was frequently missing or changed as mineral accretion insulated the cathode. This heterogeneity prevents a meaningful single "effective current" estimate. Table 1 summarizes the principal experimental datasets and the weight each can carry for the review question.

Table 1. Comparison of the principal experimental datasets relevant to continued cathodic operation. Evidentiary weight follows the appraisal described in Sections 2.4 and 2.5.

Dataset and measured outcome	Principal reported result	Interpretation for the review question	Evidentiary weight
Sabater & Yap (2002, 2004) Field; linear extension and girth	Early advantages were reported during approximately six months of power, but an overall treatment advantage was not maintained across 12 months.	Indirect treatment-package evidence; attachment, elevation, structure, and substrate were not equivalent. Low–moderate weight.	Low
Borell et al. (2010) / Romatzki (2014) Field; linear extension	Extension was highest on insulated bamboo within the electric field rather than on the cathode; high-current conditions did not improve extension. *A. yongei* cathode mortality was 32% versus 1%	One structure per electrical condition and material/attachment differences limit causal inference. Low weight for effect estimation.	Low

	in electric-field and control groups.		
Strömberg et al. (2010) Laboratory; extension and budding	Lowest-current extension was 1.27 ± 1.22 versus 1.20 ± 0.97 mm y-1 in the pre-coated no-power control; the growth-rate comparison was not significant.	Relevant pre-coated comparator, but control coating damage caused corrosion and the species was a cold-water coral. Moderate comparator relevance; null/uncertain result.	Moderate
Chavanich et al. (2013) Laboratory/field; settlement and juvenile width	No significant settlement effect was attributed to current within substrate types, and juvenile maximum width did not differ across powered current levels.	One structure represented each current level and the field study lacked a usable zero-current juvenile comparator. Low weight for incremental growth.	Low
Samidon et al. (2022) Field; two-dimensional planar growth	Branching species showed higher powered planar growth (1.10 vs 0.80 and 2.16 vs 1.68 cm2 month-1); massive species showed no significant advantage.	Only one control structure, unreported current density, and structure failures prevent fragments from serving as independent electrical replicates. Low causal weight.	Low
Cook et al. (2023) Field; survival and geometric growth	Survival was 36% on powered versus 38% on unpowered frames ($p = 0.81$); survivor-only growth showed no treatment effect ($p = 0.228$).	Three powered and three control frames, but high current, attachment damage, attrition, corrosion, and survivor-only analysis limit inference. Moderate indirect null evidence.	Moderate
Knoester et al. (2024) Field; geometric growth, bleaching, and tissue	After all tables were pre-coated, continued power produced no consistent scleractinian growth advantage. Powered tables had worse bleaching across	Closest field test of the target contrast. Common power supply, control relocation, and an early polarity error limit universality. Highest comparator directness;	Moderate

	taxa and lower final live tissue in one species.	moderate setting-specific weight.	
Kiel et al. (2026) Laboratory; corrected calcification	Adjusted means were 0.60 vs 0.38 mg cm-2 d-1 for 5-mm *P. clivosa* (significant), 0.42 vs 0.40 for 15-mm conspecifics (not significant), and 0.45 vs 0.37 for 50-mm *A. cervicornis* (not significant).	Strongest direct calcification evidence, but the control was acrylic rather than pre-coated steel and abiotic precipitation required correction. Strong narrow positive evidence; no general incremental-field inference.	Moderate

3.2 What "growth" meant in the experiments

Only Kiel et al. (2026) directly measured coral calcification in the accessible full-text core while also estimating abiotic precipitation on bare cathodes. Sabater and Yap (2002, 2004), Borell et al. (2010), Romatzki (2014), and Strömberg et al. (2010) principally used linear extension or budding. Samidon et al. (2022) used two-dimensional photographic area. Cook et al. (2023) and Knoester et al. (2024) used geometric volume or related photographic/linear estimates. These measurements describe biologically relevant changes, but none is interchangeable with total coral-produced CaCO3.

The contamination problem was quantitatively important in Kiel et al. (2026). Bare powered cathodes accumulated approximately 34.05 mg d-1 during the *A. cervicornis* experiment and 24.94 mg d-1 during the *P. clivosa* experiment, amounts much larger than the daily coral skeletal gains being estimated. The authors subtracted an abiotic-deposition estimate, but also noted that cleaning may make this estimate a lower bound. Thus, even the strongest direct calcification study required a substantial correction. Older studies that measured linear extension or used photographic or volumetric geometry avoid direct mass contamination but cannot determine whether an observed geometric increase represents greater skeletal mass, altered allocation between extension and thickening, or tissue spread.

3.3 Direct evidence for coral calcification

Kiel et al. (2026) operated steel cathodes at 1 A m-2 in flow-through laboratory aquaria and used inert acrylic pucks as controls. Microelectrode profiles showed that the elevated-pH layer was spatially restricted. At the same current density, its thickness was approximately 21 mm without flow, 15 mm at 1 cm s-1, and 6 mm at 3 cm s-1. Bulk seawater remained close to its original pH.

For 5-mm *Pseudodiploria clivosa* microfragments positioned within this boundary layer, adjusted calcification was 0.60 ± 0.22 mg cm-2 d-1 on powered cathodes compared with 0.38 ± 0.16 mg cm-2 d-1 on control pucks, a reported 43% enhancement. This percentage is retained as the authors' reported

estimate and is not recalculated from the rounded group means. Planar tissue growth was also approximately 52–53% higher. However, 15-mm fragments above the enhanced layer showed no calcification benefit: 0.42 ± 0.16 versus 0.40 ± 0.15 mg cm-2 d-1. Similarly, 50-mm *Acropora cervicornis* fragments showed an adjusted mean of 0.45 ± 0.21 versus 0.37 ± 0.26 mg cm-2 d-1, a non-significant difference.

This experiment provides the strongest explicit evidence that cathodic operation can increase coral-produced calcification. Its inference is nevertheless narrow. It demonstrates a short-term response in very small *P. clivosa* fragments within a measured low-flow chemical boundary layer. It does not show that a mineral-coated steel substrate benefits from continued power compared with the same substrate after disconnection, because the control was acrylic rather than coated steel. The *P. clivosa* experiment also used two treatment and two control aquaria, and the abiotic-deposition correction introduced additional uncertainty.

Figure 1 compares the three directly measured calcification conditions in Kiel et al. (2026). The numerical contrast is visible, but only the 5-mm *P. clivosa* comparison was statistically significant.

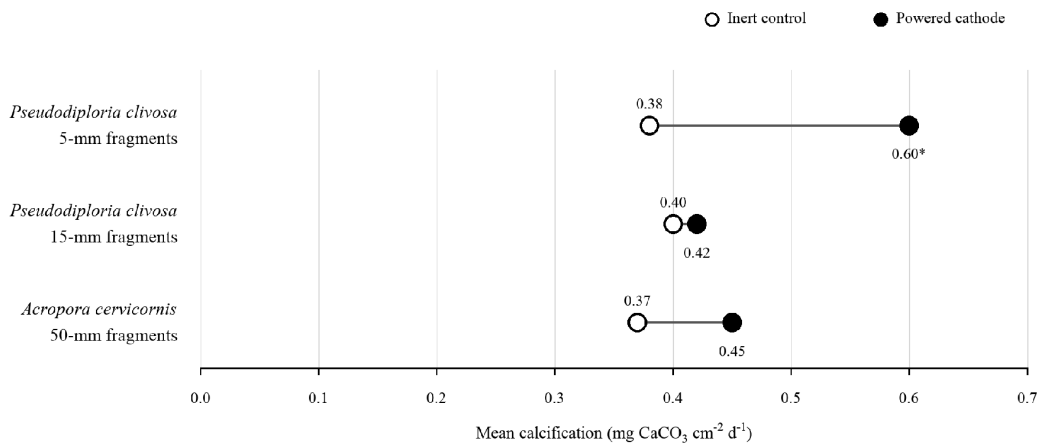


Figure 1. Direct calcification outcomes reported by Kiel et al. (2026). Values are reconstructed from Figures 3–4 and the accompanying results; powered means were corrected for reported abiotic precipitation. The asterisk marks the only significant powered-versus-control comparison (5-mm P. clivosa, $p < 0.05$). The 15-mm P. clivosa and 50-mm A. cervicornis comparisons were not significant. The article-reported 43% enhancement is retained in the text and is not recalculated from these rounded group means.

Because the plotted means are rounded reconstructions from the published figures and results, calculations based on these displayed values may not reproduce the authors' reported 43% enhancement exactly; the reported effect size is therefore retained rather than recalculated from the rounded means.

The public abstract of Huang et al. (2020) reports that low current increased *Galaxea fascicularis* calcification through 30 days but that the difference was no longer significant after a longer exposure. Because the full methods and results were unavailable, that report was not used to strengthen or weaken the methods-level conclusion. Its time-dependent abstract result is consistent with the need for full-text verification rather than evidence of a durable effect.

3.4 Evidence from the most direct substrate controls

Knoester et al. (2024) came closest to the ideal field comparison. Eighteen iron tables were powered for one month to develop a calcium-carbonate coating; nine remained powered and nine were disconnected. Across three separable scleractinian species, continued operation at 0.84 A m-2 produced no consistent geometric-growth advantage over the coated power-off controls during one year. The study also experienced a marine heatwave. Bleaching was more severe on powered tables across the four studied taxa, and final live tissue in *P. cylindrica* was lower under continued power, although tissue condition in *Acropora verweyi* did not differ. These secondary outcomes do not prove universal harm, but they prevent a claim that continued power was biologically beneficial overall under the tested conditions.

This study's comparator is relevant, but its inference is not perfect. Control tables were moved approximately 35 m, an early polarity reversal affected some controls, and one common power arrangement meant the electrical treatment was not independently replicated in the strongest possible sense. Growth was also estimated geometrically rather than as calcification. The defensible interpretation is therefore that the study supplies the best field evidence presently available against a general incremental growth benefit at 0.84 A m-2 in that Kenyan setting; it does not prove that every configuration is ineffective or harmful.

Strömberg et al. (2010) included a pre-precipitated aragonite substrate without current and several powered treatments in a six-month laboratory experiment on the cold-water coral *Lophelia pertusa*. Mean extension in the lowest-current treatment was 1.27 ± 1.22 mm y-1 compared with 1.20 ± 0.97 mm y-1 in the control, and the growth-rate analysis was not significant. Budding differed across all treatments, but the reported low-current versus control pair was not significant. Zero mortality occurred in both the control and lowest-current groups. The pre-coated no-power treatment was methodologically valuable, yet damage to its coating exposed steel and caused corrosion. The result therefore does not demonstrate an incremental extension benefit, and transfer to tropical symbiotic corals is limited.

Taken together, the two studies with the closest pre-coated comparisons do not establish a general skeletal-growth advantage from continued operation. This result is more informative for the approved RQ than simply counting all positive and negative reports.

3.5 Indirect field evidence

The accessible 2004 follow-up to the Sabater and Yap (2002, 2004) Philippine program reported an early growth advantage for *Porites cylindrica* transplants during approximately six months of active mineral accretion, followed by convergence after power was discontinued. Across the longer 12-month analysis, an overall treatment advantage was not maintained. Survival patterns suggested that secure attachment or substrate position could be important. Because powered and comparison corals also differed in attachment, structure, elevation, or substrate context, this program supports a possible temporary treatment-package effect but does not isolate continued electrochemical operation.

In the experimental program reported by Romatzki (2014), higher-current conditions did not improve *Acropora* extension. *A. yongei* grew more slowly on the approximately 2.38 A m-2 structure than under the lower-current or control conditions. In the four-month experiment also reported by Borell et al. (2010), both *A. yongei* and *A. pulchra* had the highest extension on insulated bamboo situated inside the electric field rather than on the cathode itself. *A. yongei* cathode mortality reached 32%, compared with 1% for both the electric-field and control groups. The pattern is inconsistent with a simple explanation in which direct cathodic mineral accretion universally accelerates growth. However, one structure per electrical condition and differences in material and attachment create pseudoreplication and confounding. The studies are more useful for challenging overgeneralization than for estimating a precise causal effect.

Samidon et al. (2022) followed two branching and two massive species on three powered structures and one unpowered structure in Indonesia. Powered branching corals showed higher two-dimensional planar growth—1.10 versus 0.80 cm2 month-1 for *Acropora gemmifera* and 2.16 versus 1.68 cm2 month-1 for *Pocillopora verrucosa*—whereas the two massive *Porites* species did not show significant advantages. Survival did not differ by treatment. This apparently morphology-dependent result is relevant, but there was only one control structure, current density was not reported, one cable failed, and one powered structure later overturned. Analysing fragments as replicates cannot repair the absence of replicated control structures. The study therefore supplies a positive hypothesis for branching planar growth, not strong evidence of a general electrical effect.

Chavanich et al. (2013) tested larval settlement in aquaria and monitored naturally recruited juvenile *Pocillopora damicornis* on four pre-existing field structures. In the laboratory, settlement tended to be highest on coralline-algal tiles and limestone-encrusted steel without current; the authors reported no significant settlement difference attributable to current level within substrate types. In the four-month field component, juvenile maximum width did not differ among 0.4, 0.65, and 0.9 A m-2 structures, while survival was highest at the lowest current and lowest at the highest. No juveniles were available for monitoring on the unpowered structure, leaving no usable zero-current field comparator. Because one structure represented each current level and naturally settled juveniles were subsamples, the field data cannot estimate a replicated current effect. The study is therefore informative as a warning against assuming monotonic benefit and as evidence that an already encrusted unpowered substrate can support settlement, but not as a direct test of incremental skeletal growth.

Cook et al. (2023) used three powered and three unpowered steel frames at Agincourt Reef on the Great Barrier Reef. At an estimated actual current density of approximately 4.3 A m-2, survival was 36% on powered and 38% on unpowered frames ($p = 0.81$), and survivor-only geometric growth showed no treatment effect ($p = 0.228$). Unpowered steel corroded while powered steel acquired a substantial coating. Because corrosion should have disadvantaged the controls, the lack of benefit is notable. Still, the high current, attachment damage, missing fragments, and survivor-only growth analysis prevent this study from specifying what would occur under lower current with a stable pre-coated control.

3.6 Conditions that explain part of the disagreement

The clearest supported condition is not species identity or current density alone, but whether actively calcifying tissue remains within the altered chemical microenvironment. Kiel et al. (2026) directly linked boundary-layer height to biological response: 5-mm *P. clivosa* benefited, while 15-mm conspecifics and 50-mm *A. cervicornis* did not. Increasing flow compressed the layer from approximately 15 mm at 1 cm s-1 to approximately 6 mm at 3 cm s-1. This makes fragment geometry, tissue height, flow, cathode shape, and current density interacting conditions rather than independent explanations.

Current effects were non-monotonic across the literature. Low-current treatments sometimes produced favorable or neutral responses, whereas high-current treatments in Romatzki (2014), Strömberg et al. (2010), and Cook et al. (2023) did not yield convincing benefits. A larger current may produce more hydroxide, but it also accelerates abiotic precipitation, changes mineral composition, and may insulate the cathode. The present data do not identify a universal optimum because current at the coral surface was often missing, declined over time, or was not independently replicated.

Duration was recorded for each experiment and considered during evidence weighting, but the heterogeneous designs and outcomes did not permit a duration-adjusted estimate. The Sabater and Yap program and the abstract of Huang et al. (2020) suggest that early differences may weaken with time. Cathode insulation and coral growth beyond a thin boundary layer provide possible mechanisms, but the accessible studies do not separate these explanations experimentally over long periods.

Species and morphology modify response, but the evidence is not sufficient to rank taxa. Samidon et al. found a planar-area benefit in branching but not massive corals, while Kiel et al. found a calcification benefit in short massive microfragments but not taller branching fragments. These results are not contradictory once measurement, size, flow and control design are considered. They show why “branching versus massive” is too coarse to function as a general rule.

3.7 Sensitivity of the conclusion to evidence quality

An unweighted reading of the literature can support the statement that results are “mixed”: some reports describe greater extension or planar area, whereas others report null or adverse outcomes. That summary is unstable because it gives equal weight to non-equivalent outcomes and causal contrasts.

Restricting the evidence to direct, abiotic-deposition-corrected calcification leaves the Kiel et al. (2026) experiments. In that study, the positive effect occurs in one of three tested species-or-height conditions

and is spatially aligned with the measured boundary layer. Restricting the evidence instead to the closest tests of continued power after coating leaves Knoester et al. (2024) and, less cleanly, Strömberg et al. (2010); neither establishes a general incremental skeletal-growth advantage. Adding weaker field comparisons increases the number of favorable observations, but it also reintroduces substrate, corrosion, attachment, structure, site, and treatment-unit confounding.

The central conclusion is therefore robust to the two restrictions most relevant to the RQ: mechanistic possibility is supported, but general incremental biological effectiveness is not. This is a qualitative sensitivity analysis, not a statistical meta-analysis, and it cannot estimate an average effect size.

4. DISCUSSION

4.1 Direct answer to the research question

The experimental evidence for an incremental biological benefit of continued externally powered cathodic operation is limited and conditional. A short-term increase in coral-produced calcification has been demonstrated for 5-mm *P. clivosa* microfragments located inside a measured elevated-pH boundary layer. The same experiment found no benefit for taller conspecific or *A. cervicornis* fragments outside that layer. The closest pre-coated field comparison found no consistent scleractinian geometric-growth benefit from continued power. Older positive reports mainly used extension or planar geometry and controls that combined continued operation with coating, corrosion protection, attachment, structure, elevation, or site.

Therefore, the literature supports the existence of a local electrochemical mechanism capable of increasing calcification under bounded conditions. It does not presently establish that keeping a mineral-accreted restoration structure powered generally increases coral calcification or skeletal growth beyond the value of the coating and physical substrate.

4.2 Why measurement changes the conclusion

If all author-labelled “growth” outcomes are treated as equivalent, the literature appears internally inconsistent: some studies report positive outcomes, while others report null results or adverse outcomes such as higher mortality and worse bleaching or tissue condition. That framing invites an unsatisfactory conclusion that results are merely “mixed.” Reclassification changes the inference. The only accessible full-text experiment measuring calcification with an abiotic-deposition correction produced one positive and two null species/height conditions. The older favorable field evidence measured extension or planar area and cannot determine how much additional coral skeleton was produced.

This does not make extension or tissue area unimportant. Extension can increase habitat complexity, and tissue spread can improve microfragment fusion. The error occurs only when those outcomes are used as direct evidence for greater calcification or for restoration success. A publication-quality claim must name the measured outcome and avoid moving upward from a fragment-level proxy to survival, recruitment, reef function or self-sustaining recovery.

4.3 Why control design changes the conclusion

The ideal question concerns a component effect: what does continued operation add after the substrate is already mineral-accreted? Most experiments instead test a bundle. Powered steel is compared with bare steel, bamboo, acrylic, natural reef, or a different location. Any difference may then reflect electricity, local chemistry, mineral coating, reduced corrosion, attachment, elevation, or environmental exposure.

When greater weight is assigned to the controls closest to the target comparison, support for a general benefit weakens. Knoester et al. (2024) found no consistent scleractinian growth advantage after all structures were initially coated. Strömberg et al. (2010) also found no significant growth advantage against its no-power controls, although corrosion weakened that comparison. This evidence does not invalidate the narrow Kiel effect because the experiments tested different geometry, flow, species, duration, and outcomes. Instead, it defines the boundary between mechanistic possibility and field-level generalization.

True replication is equally important. When power is assigned to a whole frame, the frame or independently powered circuit, not each attached fragment, is the treatment unit. Samidon et al. had only one control structure, and important Romatzki experiments had one structure per electrical condition. Large fragment counts can estimate variation among corals on a structure, but they cannot show that the treatment would reproduce across structures or sites.

4.4 Mechanistic interpretation

The cathodic mechanism is chemically plausible and now partly demonstrated. Lees et al. (2024) modeled increases in pH, carbonate concentration and aragonite saturation close to cathodes. Kiel et al. (2026) directly measured the boundary layer and connected its vertical extent with a calcification response. This is stronger than inferring a mechanism from favorable field growth alone.

Two recent non-electrochemical experiments help separate an alkalinity response from an electricity-specific effect. Cooke et al. (2026) used dissolved sodium bicarbonate and sodium carbonate rather than a cathode and found that 33 days of elevated bulk alkalinity increased *Acropora cervicornis* calcification, with a maximum reported increase of 125%. Ruszczyk et al. (2026) instead used carbonate-modified cement tiles that elevated pH within a near-substrate boundary layer; tile chemistry influenced post-settlement survivorship of *Orbicella faveolata* recruits but did not significantly affect their measured skeletal growth over 139 days. These studies support the broader biological relevance of altered carbonate chemistry while also showing that the source, spatial extent, duration, life stage and measured outcome matter. Neither study tests whether continued cathodic power adds a benefit beyond a mineral-accreted substrate.

The same mechanism explains important limitations. Flow disperses hydroxide and compresses the favorable layer. Abiotic mineral precipitation consumes electrochemically generated alkalinity, changes cathode resistance, and can dominate mass measurements. As a fragment grows taller, its active tissue

may leave the enhanced region. A system can therefore deposit large amounts of mineral on steel without producing a sustained biological advantage to the coral above it.

Mechanistic support should not be confused with environmental safety. Kiel et al. physically removed anode products from its coral system, whereas open-field designs may distribute acidity or oxidants differently. Knoester et al. observed worse bleaching or tissue outcomes in some conditions. These observations justify measuring anode chemistry and coral condition in future experiments; they do not yet justify a universal safety or harm claim.

4.5 What limits generalizability

The strongest positive result cannot as of yet be generalized by a simple appeal to species or current density. Its effect depended on a measured spatial relationship: living tissue remained inside a thin elevated-pH layer under low flow. Hydrodynamics can compress that layer, growth can move tissue beyond it, and cathode geometry can change local current distribution. These linked physical conditions are more directly supported than a universal "low current is beneficial" rule.

Biological coverage is also narrow. The experiments use a limited set of species, life stages, fragment sizes and morphologies, often over weeks or months. Genotype, symbiont community, heterotrophic capacity, tissue thickness, skeletal architecture, and prior stress could alter response, but current studies do not isolate those moderators. A result in a 5-mm massive-coral microfragment therefore cannot be projected to a mature colony or a branching transplant without new evidence.

Finally, field generalization is restricted by study design. Several treatments were represented by one structure or one electrical system; many positive results used indirect geometric outcomes or non-equivalent controls; and electrical exposure at coral-tissue height was often unreported. The present evidence can identify a plausible boundary condition, but it cannot supply a universal operating range or a transferable average benefit.

4.6 Relationship to the previous scoping review

Rivas-Mena et al. (2026) showed that the wider mineral-accretion literature has weak controls, inconsistent terminology, and inadequate reporting. The present synthesis confirms that problem for coral experiments but comes to a different conclusion. The decisive issue is not only whether a control exists; it is what biological outcome and causal effect that control can identify. Separating calcification from extension and geometry, correcting for abiotic deposition, reconstructing shared datasets, and prioritizing the coated power-on versus power-off contrast changes the scientific answer from "mixed reported effects" to "one narrow demonstrated effect without a general incremental field benefit."

4.7 Decision relevance without a deployment claim

The evidence is strong enough to change how continued electrical operation should be treated in future conservation decisions. It should not be assumed to be the active ingredient merely because a powered frame becomes mineral-coated or because attached corals survive. Instead, continued operation is a

separable, testable component whose biological benefit must be demonstrated against an equivalent coated power-off condition.

This conclusion is relevant to any future site-specific appraisal, including one in Okinawa, because it prevents premature commitment to power infrastructure before incremental benefit is established. It does not determine Okinawa's suitability. That latter question would require local hydrodynamics, temperature and bleaching exposure, species and genotypes, typhoon engineering, anode and material risks, energy and maintenance demands, permits, stakeholder responsibilities, and comparison with non-electrochemical restoration options. The present review supplies an evidence gate, not a site verdict.

4.8 Minimum design for a decisive experiment

A future experiment capable of answering the RQ should include the following minimum design requirements:

• **Equivalent pre-accreted controls:** Randomize equivalent pre-accreted cathodes to continued-power and power-off groups. A bare-metal group may be added to quantify coating and corrosion effects, but it cannot replace the pre-coated control.

• **Independent treatment replication:** Use multiple independently powered systems so that the electrical treatment itself is independently replicated.

• **Balanced coral allocation:** Balance corals across treatments by genotype, species, initial size, attachment method, height and position.

• **Direct calcification measurement:** Measure coral-produced calcification using buoyant weighing or another validated skeletal-mass technique.

• **Abiotic-deposition blanks:** Include bare-cathode blanks and a prespecified correction for abiotic deposition.

• **Coral-tissue-height chemistry:** Measure current density and electrode potential over time and measure pH and carbonate chemistry at the height of living coral tissue under representative flow, not only at the cathode surface.

• **Anode chemistry and system monitoring:** Record anode products, corrosion and system failures.

• **Duration and stopping criteria:** Continue the experiment long enough to test cathode insulation and growth beyond the boundary layer, with prespecified stopping criteria.

Linear extension, three-dimensional geometry, tissue area, density, survival and photophysiology should be recorded separately rather than combined into a single growth score.

This design would test a scientific uncertainty. It is not, by itself, a recommendation to deploy a restoration system.

4.9 Limitations of this review

This review used a targeted critical-search strategy rather than a systematic-review protocol, so relevant studies may have been missed. One apparently relevant calcification article, Huang et al. (2020), was available only as an abstract and was not used for detailed appraisal. Publication bias is possible because unsuccessful projects may remain unpublished. No dedicated search was conducted for non-English studies, technical reports, or unpublished restoration projects, so relevant evidence from these sources may also have been missed. The small evidence base and heterogeneous methods prevented meta-analysis. Several electrical exposures were incompletely reported, and some papers did not permit reconstruction of the true treatment-level variance. Study selection and extraction were conducted by one reviewer, which increases the risk of classification or extraction error.

The evidence is also biologically narrow. Most studies used transplanted fragments rather than natural recruitment or population-level recovery. Short-term calcification or extension cannot establish reproductive success, biodiversity, ecological function, or a self-sustaining reef. No inference about Okinawa-specific suitability, lifecycle sustainability, permitting, typhoon resilience, material release or cost follows from this review.

5. CONCLUSION

Continued externally powered cathodic operation can increase scleractinian coral calcification, but the scope of the demonstrated effect is narrow: it occurred in very small *Pseudodiploria clivosa* fragments that remained within a measured low-flow elevated-pH boundary layer for 60 days. It was absent in taller conspecifics and *Acropora cervicornis* under the same study, while the closest coated power-on versus power-off field experiment found no consistent scleractinian geometric-growth benefit. Most other positive reports measured extension or planar geometry and used controls that could not isolate continued operation from mineral coating, corrosion protection, attachment, structure or site.

The strongest defensible conclusion is therefore not that the method universally succeeds or fails. It is that a conditional local biological mechanism is supported, whereas a general incremental benefit of keeping mineral-accreted field structures powered is not established by the present evidence. Reported benefits cannot yet be generalized beyond their tested fragment geometry, flow, duration, taxa and system design. Until replicated experiments combine equivalent pre-coated controls with direct, abiotic-deposition-corrected calcification measurements, continued power should be treated as an experimental variable requiring justification rather than an assumed requirement for coral restoration.

REFERENCES

Borell, E. M., Romatzki, S. B. C., & Ferse, S. C. A. (2010). Differential physiological responses of two congeneric scleractinian corals to mineral accretion and an electric field. *Coral Reefs, 29*, 191–200. https://doi.org/10.1007/s00338-009-0564-y

Boström-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S. C. A., Hancock, B., Harrison, P., Hein, M., Shaver, E., Smith, A., Suggett, D., Stewart-Sinclair, P. J., Vardi, T., & McLeod, I. M. (2020). Coral restoration—A systematic review of current methods, successes, failures and future directions. *PLOS ONE, 15*(1), e0226631. https://doi.org/10.1371/journal.pone.0226631

Chavanich, S., Ussavauschariyakul, S., Viyakarn, V., & Fujita, T. (2013). Influence of mineral accretion induced by electric current on the settlement and growth of the scleractinian coral *Pocillopora damicornis* (Cnidaria, Anthozoa, Hexacorallia). *Marine Research in Indonesia, 38*(2), 89–94. https://doi.org/10.14203/mri.v38i2.60

Cohen, S., Krueger, T., & Fine, M. (2017). Measuring coral calcification under ocean acidification: Methodological considerations for the 45Ca-uptake and total alkalinity anomaly technique. *PeerJ, 5*, e3749. https://doi.org/10.7717/peerj.3749

Cook, N., Cook, K., Harris, K. J., Songcuan, A., & Smith, A. K. (2023). Lessons learned implementing mineral accretion and coral gardening at Agincourt Reef, Great Barrier Reef. *Ecological Management & Restoration, 24*(2–3), 107–118. https://doi.org/10.1111/emr.12585

Cooke, K. M., Palacio-Castro, A. M., Boyd, A., Soderberg, N., Kiel, P. M., Stevens, A., Langdon, C., & Enochs, I. C. (2026). Alkalinity enrichment stimulates calcification and linear extension in *Acropora cervicornis*. *Scientific Reports, 16*, 14512. https://doi.org/10.1038/s41598-026-44817-6

Gómez Batista, M., Metian, M., Oberhänsli, F., Pouil, S., Swarzenski, P. W., Tambutté, E., Gattuso, J.-P., Alonso Hernández, C. M., & Gazeau, F. (2020). Intercomparison of four methods to estimate coral calcification under various environmental conditions. *Biogeosciences, 17*, 887–899. https://doi.org/10.5194/bg-17-887-2020

Huang, B., Yuan, T., Liang, Y., Guo, Y., Yuan, X., Zhou, W., Huang, H., & Liu, S. (2020). Low electric current density enhances the calcification rate of the colonial stony coral *Galaxea fascicularis*. *Aquatic Ecosystem Health & Management, 23*(3), 332–340. https://doi.org/10.1080/14634988.2020.1768766

Hurlbert, S. H. (1984). Pseudoreplication and the design of ecological field experiments. *Ecological Monographs, 54*(2), 187–211. https://doi.org/10.2307/1942661

Kiel, P. M., McConnell, M., Boyd, A., Soderberg, N., Suraneni, P., Prakash, V. N., & Enochs, I. C. (2026). Electrochemically induced alkalinity enhancement increases coral growth rates in the local microenvironment. *Coral Reefs, 45*, 737–752. https://doi.org/10.1007/s00338-025-02791-x

Kihara, K., Taniguchi, H., Koibuchi, Y., Yamamoto, S., Kondo, Y., & Hosokawa, Y. (2013). Enhancing settlement and growth of corals using feeble electrochemical method. *Galaxea, Journal of Coral Reef Studies, 15*, 323–329. https://doi.org/10.3755/galaxea.15.323

Knoester, E. G., Sanders, R., Durden, D., Masiga, B. O., Murk, A. J., & Osinga, R. (2024). Negative effects by mineral accretion technique on the heat resilience, growth and recruitment of corals. *PLOS ONE, 19*(12), e0315475. https://doi.org/10.1371/journal.pone.0315475

Lees, E. W., Tournassat, C., Weber, A. Z., & Gilbert, P. U. P. A. (2024). eCoral: How electrolysis could restore seawater conditions ideal for coral reefs. *The Journal of Physical Chemistry Letters, 15*, 12206–12211. https://doi.org/10.1021/acs.jpclett.4c02715

Rivas-Mena, G., Ruiz-Frau, A., Hinz, H., Djordjevic, N., Djurovic, M., & Mačić, V. (2026). Assessing the mineral accretion technique (MAT) for marine benthic restoration: A scoping review highlighting procedural weaknesses and evidence gaps. *PeerJ, 14*, e21440. https://doi.org/10.7717/peerj.21440

Romatzki, S. B. C. (2014). Influence of electrical fields on the performance of *Acropora* coral transplants on two different designs of structures. *Marine Biology Research, 10*(5), 449–459. https://doi.org/10.1080/17451000.2013.814794

Ruszczyk, M., Rodriguez, S., Tuen, M., Rux, K., Paul, V., Chandragiri, S., Stickley, M., Swart, P. K., Haus, B. K., Baker, A. C., Miller, M. W., Suraneni, P., Langdon, C., & Prakash, V. N. (2026). Alkalinity-enhanced artificial substrates modulate local pH and increase survivorship of early-stage coral recruits. *Communications Earth & Environment, 7*, 311. https://doi.org/10.1038/s43247-026-03414-1

Sabater, M. G., & Yap, H. T. (2002). Growth and survival of coral transplants with and without electrochemical deposition of CaCO3. *Journal of Experimental Marine Biology and Ecology, 272*(2), 131–146. https://doi.org/10.1016/S0022-0981(02)00051-5

Sabater, M. G., & Yap, H. T. (2004). Long-term effects of induced mineral accretion on growth, survival and corallite properties of *Porites cylindrica* Dana. *Journal of Experimental Marine Biology and Ecology, 311*, 355–374. https://doi.org/10.1016/j.jembe.2004.05.013

Samidon, M., Razi, N. M., Agustiar, M., Harahap, P. B., Najmi, N., Bahri, S., & Liu, S. Y. V. (2022). In-situ electro-stimulation enhanced branching but not massive scleractinian coral growth. *Frontiers in Marine Science, 9*, 917360. https://doi.org/10.3389/fmars.2022.917360

Strömberg, S. M., Lundälv, T., & Goreau, T. J. (2010). Suitability of mineral accretion as a rehabilitation method for cold-water coral reefs. *Journal of Experimental Marine Biology and Ecology, 395*, 153–161. https://doi.org/10.1016/j.jembe.2010.08.028

Tambutté, S., Holcomb, M., Ferrier-Pagès, C., Reynaud, S., Tambutté, É., Zoccola, D., & Allemand, D. (2011). Coral biomineralization: From the gene to the environment. *Journal of Experimental Marine Biology and Ecology, 408*(1–2), 58–78. https://doi.org/10.1016/j.jembe.2011.07.026

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