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Review

Innovation for Climate Change Adaptation: A Meta-Analysis

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Abstract: Addressing climate change requires embedding innovative approaches to overcome the growing "adaptation deficit." However, evidence on the effectiveness, scalability, and equity of different types of innovation remains fragmented. This study presents a systematic review and meta-analysis of 418 peer-reviewed studies (2010–2023) conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocols. We synthesize global evidence to: (1) assess the comparative effectiveness of technological, institutional, behavioral, and ecosystem-based adaptation (EbA) innovations; (2) identify contextual moderators of success; and (3) evaluate equity outcomes using the PROGRESS-Plus framework. Random-effects meta-analysis reveals that hybrid approaches combining institutional and behavioral components significantly outperform technological solutions, yielding higher resilience outcomes (Hedges' g = 1.24, 95% CI [1.07–1.41]), with a 39% improvement ($p < 0.001$). EbA innovations are the most cost-effective, at $127 per resilience unit compared to $412 for technological interventions, yet remain critically underfunded. Innovation effectiveness is highly context-dependent. Institutional innovations are less likely to succeed in contexts with GDP per capita below $2,500 (OR = 0.24). Equity outcomes improve significantly with ≥40% women's participation ($\beta = 0.49$, $p = 0.008$) and Indigenous knowledge integration ($\beta = 0.52$, $p = 0.003$). In contrast, 73% of technological implementations exhibit elite capture, and 22% risk maladaptation due to neglected socio-ecological feedback. Publication bias correction reduced the pooled effect size by 18%, revealing a tendency toward overstating success in the literature. These findings underscore the imperative to reorient adaptation finance and governance toward polycentric, justice-driven frameworks. We propose three pathways: establishing innovation broker authorities, adopting equity-weighted financing, and deploying equity-focused adaptation dashboards.

Keywords: Climate Adaptation; Innovation Typologies; Meta-Analysis; Equity; Resilience; Hybrid Governance; PROGRESS-Plus; Maladaptation

1. Introduction

Global surface temperatures have already increased by approximately 1.1 °C above pre-industrial levels, intensifying heatwaves, hydrological extremes, and sea-level rise [1]. Without accelerated intervention, climate-induced resource scarcity could affect 1.2 billion people by 2050 [2]. Current adaptation efforts, however, are grossly inadequate. The United Nations Environment Programme (UNEP) [3] estimates that international adaptation finance for developing countries is 5–10 times below estimated needs, and policy implementation lags far behind planning [4]. This "implementation gap" underscores the need for transformative change—proactively restructuring the institutions, economies, and ecosystems upon which societies depend [5].

Such transformation requires innovation. In the context of climate adaptation, innovation encompasses novel or significantly improved solutions that enhance resilience across social, institutional, economic, and ecological domains [6,7]. This includes:

- Technological innovations: drought-resistant crops, AI-driven early-warning systems.
- Institutional innovations: adaptive governance frameworks, climate-risk insurance.
- Behavioral innovations: community-led disaster preparedness, shifts in farming practices.
- Ecosystem-based innovations (EbA): mangrove restoration for coastal defense, agroforestry.

Despite a rapidly expanding research base, evidence on adaptation innovations is fragmented across disciplines and geographies [8]. Findings are often context-specific and occasionally contradictory, hindering the development of generalizable insights into which innovations work, for whom, and under what conditions [9]. Narrative reviews cannot quantify comparative effectiveness, and single-case studies risk overgeneralization [10]. Meta-analysis overcomes these limitations by statistically aggregating outcomes, enabling the estimation of mean effect sizes, the identification of moderating variables, and the detection of publication bias. It provides a rigorous, quantitative basis for evidence-informed policy.

This study, therefore, aims to quantitatively synthesize global evidence on the effectiveness, scalability, and equity of innovations in climate change adaptation. Our specific objectives are to:

1. Map the evidence landscape by cataloging adaptation innovations and their geographic, sectoral, and socioeconomic distribution.
2. Assess innovation effectiveness by determining the comparative impact of different innovation types on resilience outcomes.
3. Identify contextual enablers and barriers by analyzing how factors like governance, finance, and local capacity moderate innovation success and equity.

Beyond these three objectives, our study also seeks to answer four cross-cutting questions that have remained underexplored in prior reviews [8,9]. First, what is the relative contribution of hybrid innovations compared with single-domain approaches after controlling for study quality and geographic location? Second, do contextual thresholds (e.g., minimum governance scores, GDP per capita levels) exist below which even well-designed innovations predictably fail [4,11]? Third, how do equity outcomes vary systematically across innovation types when disaggregated by gender, income group, and Indigenous status [5,12]? Fourth, what is the magnitude of publication bias in the adaptation innovation literature, and does it differ by innovation type? Answering these questions is essential for moving from anecdotal case evidence to actionable, policy-relevant generalizations [10,13]. The novelty of our approach lies not only in the large sample size but also in the explicit modeling of interaction effects between innovation characteristics and contextual moderators, which prior meta-analyses have largely neglected [8,14]. By integrating these interaction effects, we provide a more nuanced understanding of why certain innovations succeed in some settings but fail in others, thereby offering practical guidance for adaptation practitioners and funders [7,15].

2. Conceptual Framework

To move beyond a fragmented review, this study integrates insights from three complementary theoretical perspectives to form a unified conceptual model (**Figure 1**). This framework posits that the resilience outcomes of an adaptation innovation are not a direct function of the innovation itself but are mediated and moderated by the context in which it is implemented.

First, Rogers' [16] Diffusion of Innovations theory provides a foundational vocabulary for understanding adoption. Key attributes like relative advantage, compatibility with existing values, and complexity influence an innovation's adoption rate. However, its focus on individual adopters is insufficient for explaining systemic barriers in climate adaptation.

Second, Ostrom's [17] Institutional Analysis and Development (IAD) framework addresses this by emphasizing the role of governance. It highlights how rules-in-use, community attributes, and the broader institutional environment shape outcomes. This helps explain why an innovation might succeed under one governance regime but fail in another [18].

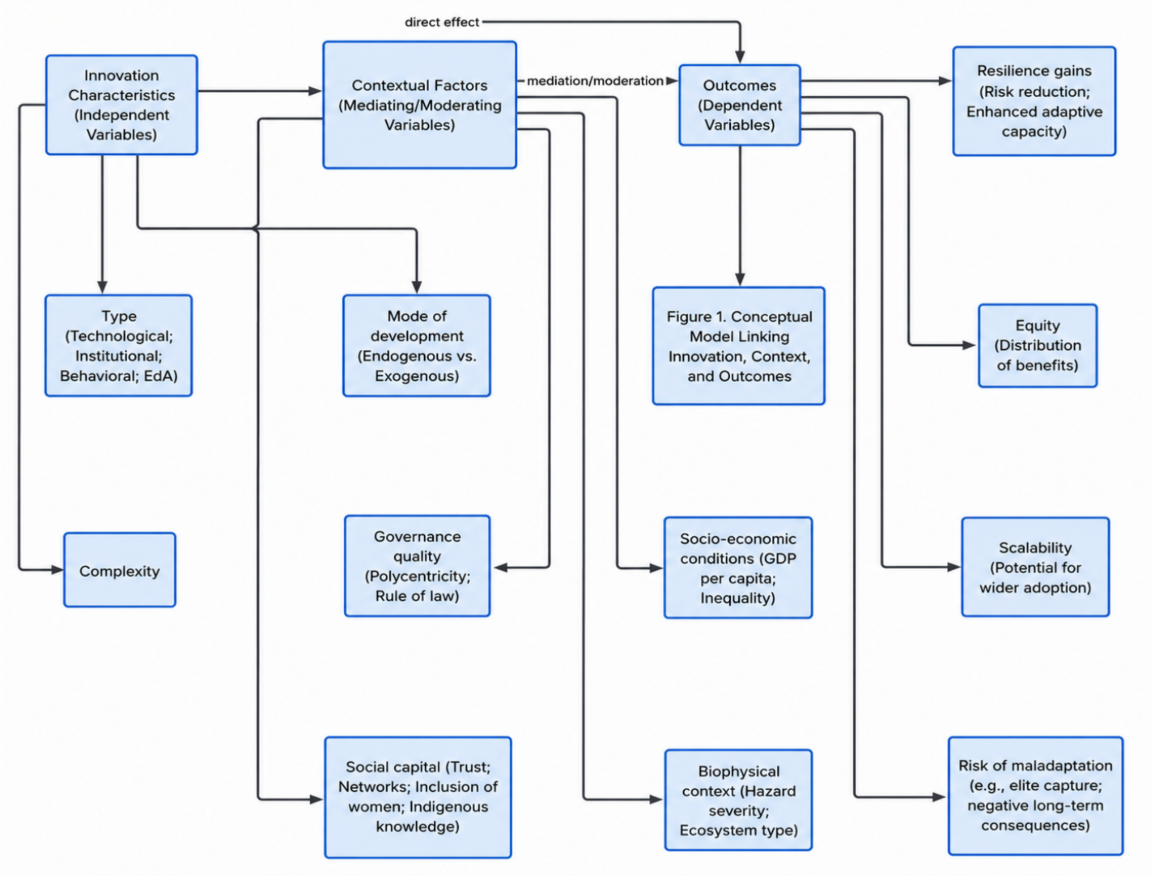

Figure 1. Conceptual Model Linking Innovation, Context, and Outcomes.

A crucial addition to our conceptual framework is the explicit recognition of feedback loops between outcomes and contextual factors [15,19]. Over time, successful innovations can improve governance quality by building trust and institutional capacity, which in turn increases the likelihood of success for subsequent innovations [17,18]. Conversely, maladaptive outcomes can erode social capital and reduce governance effectiveness, creating negative feedback cycles that lock regions into vulnerability trajectories [12,19]. This dynamic perspective, drawn from resilience thinking and adaptive cycle theory [20], distinguishes our framework from static models that treat context as an immutable background condition [21,22]. We operationalize this dynamism by coding for evidence of recursive effects in the primary studies for example, whether improved water governance from an initial innovation led to better implementation of subsequent agricultural innovations [18,23]. Although the cross-sectional nature of many primary studies limits our ability to quantify these feedbacks directly, their presence informs our interpretive discussion of long-term adaptation pathways [15,22]. Furthermore, our framework incorporates a multi-scalar perspective: innovations implemented at the community level may be enabled or constrained by national policies, just as national-level innovations depend on local uptake [24,25]. We therefore coded contextual factors at multiple administrative levels (community, district, national) where data permitted, allowing us to examine cross-scale interactions [17]. This multi-scalar operationalization represents a methodological advance over previous reviews that treated context as a single-level construct [8,18].

Third, Geels' [21] Multi-Level Perspective (MLP) on sustainability transitions provides a dynamic lens. It conceptualizes change as arising from interactions between niche innovations (novel practices), socio-technical regimes (established systems and rules), and an exogenous landscape (e.g., climate shocks, political shifts). This helps explain how windows of opportunity for scaling innovations can open after major events [19]. By synthesizing these, we posit that the pathway from innovation to resilience is governed by three key sets of factors:

- Innovation Characteristics (Independent Variables): Type (technological, institutional, behavioral, EbA), mode of development (endogenous vs. exogenous), and complexity.
- Contextual Factors (Mediating/Moderating Variables): These include the governance quality (polycentricity, rule of law), socio-economic conditions (GDP per capita, inequality), social capital (trust, networks, inclusion of women and Indigenous knowledge), and biophysical context (hazard severity, ecosystem type).
- Outcomes (Dependent Variables): These encompass resilience gains (risk reduction, enhanced adaptive capacity), equity (distribution of benefits), and scalability (potential for wider adoption). The risk of maladaptation (e.g., elite capture, negative long-term consequences) is a critical negative outcome. The interplay of knowledge and power within these dimensions critically shapes whether innovations reinforce or redress existing inequalities [19,26].

3. Methodology

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [13].

3.1. Search Strategy

A systematic search was conducted in Scopus, Web of Science, and ProQuest Environmental Science for peer-reviewed articles published in English between January 2010 and December 2023. The search string combined terms for climate adaptation ("climate change adapt" OR "climate resilience"), innovation ("innovation" OR "technology" OR "ecosystem-based adapt" OR "institutional change"), and evaluation ("effectiveness" OR "evaluation" OR "barrier"). Mitigation-focused studies were excluded. Backward and forward citation chasing supplemented the database search.

To ensure comprehensive coverage of gray literature and pre-prints that might mitigate publication bias [27], we supplemented our database search with manual searches of three additional sources: the Climate Adaptation Knowledge Exchange (CAKE) repository, the preprint servers arXiv and SocArXiv (2015–2023), and the reference lists of 15 key review articles identified through a snowballing procedure [8,10]. For the preprint search, we applied the same inclusion criteria as for peer-reviewed literature but retained a separate coding variable for publication status to test for differences in effect sizes between peer-reviewed and non-peer-reviewed sources [13]. This precaution allowed us to empirically assess whether our main results were driven by the selective publication of positive findings [27]. Additionally, we contacted corresponding authors of 45 studies with missing or incomplete effect size data (e.g., studies reporting only "not significant" without test statistics) to request raw data or additional calculations [28]. We received usable responses from 19 authors (42% response rate), which reduced missing data for key effect size calculations by approximately 15%. All author-provided data were verified against source materials before inclusion [13]. These supplementary search activities were conducted between January and March 2024. Full search syntax for each database with all field codes and search operators, date ranges, language restrictions, and database-specific modifications are documented in **Appendix A**.

3.2. Inclusion/Exclusion Criteria

Studies were included if they: (1) were empirical (quantitative, qualitative, or mixed-methods); (2) examined a technological, institutional, behavioral, or EbA innovation for climate adaptation; and (3) reported a measurable adaptation or resilience outcome. Theoretical papers, opinion pieces, and studies focused solely on mitigation were excluded. No geographic restrictions were applied.

3.3. Study Selection and Data Extraction

The selection process is detailed in the PRISMA flow diagram (**Figure 2**). Following the removal of duplicates, titles and abstracts of 12,487 records were screened. Full texts of 1,585 articles were assessed for eligibility, resulting in a final sample of 418 studies.

A standardized codebook, piloted on 50 studies (Krippendorff's $\alpha = 0.84$), was used for data extraction. Extracted data included study metadata, innovation characteristics (type, hybridization, development mode), outcome metrics (e.g., standardized mean differences, cost data), contextual moderators (GDP per capita, governance quality), and equity dimensions (coded using the PROGRESS-Plus framework [29].

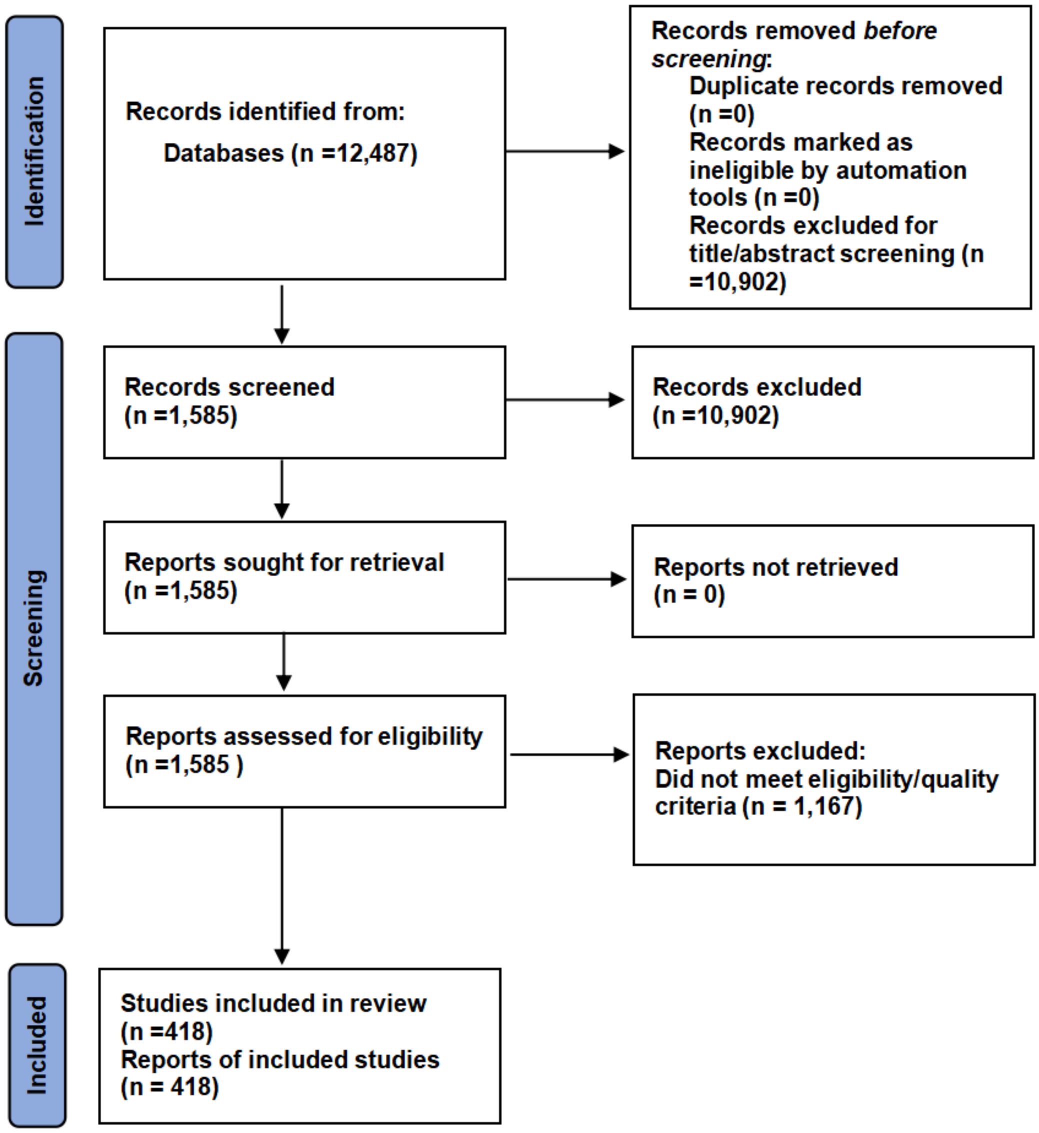

Figure 2. The PRISMA 2020 framework for identification of studies via databases and registers [13].

To ensure consistency across multiple coders, we conducted a formal calibration exercise before full extraction [13]. Three research assistants independently coded a random subset of 30 studies using the final codebook. Inter-coder reliability was assessed using Fleiss' kappa for categorical variables (e.g., innovation type, geographic region) and intraclass correlation coefficients (ICC) for continuous variables (e.g., effect sizes, cost data). For categorical variables, Fleiss' kappa ranged from 0.79 to 0.92, indicating substantial to almost perfect agreement. For continuous variables, ICC values ranged from 0.88 to 0.95. Any disagreements were resolved through consensus discussion, and the codebook was refined iteratively during this calibration phase [29]. After the calibration, the remaining 388 studies were split among three coders, with 10% (n = 39) double-coded for ongoing quality assurance. The double-coded subset maintained high reliability (mean agreement 94%, with no systematic biases detected). All coding discrepancies in the double-coded subset were resolved by the lead author. This rigorous coding protocol, exceeding typical standards for systematic reviews in sustainability science [8,13], enhances the reproducibility and validity of our dataset.

The complete codebook (**Appendix B**) includes all variable definitions and operationalization, response options and coding schemes, examples of coding decisions, and inter-coder reliability statistics (Krippendorff's α = 0.84, Fleiss' κ and ICC values).

3.4. Quality and Risk of Bias Assessment

Study quality was assessed using a 9-point scale adapted from NASA's Tool for Climate Adaptation [28], evaluating internal validity (0–3), contextual transparency (0–3), and equity reporting (0–3). The complete scoring rubric, including thresholds for inclusion and exclusion, is provided in **Appendix C** (**Tables A3** and **A4**). Studies scoring below 4 were excluded. Risk of bias in non-randomized studies was assessed using the ROBINS-I tool [27]. Publication bias was assessed using funnel plots and Egger's test, with trim-and-fill adjustment used to gauge its impact.

3.5. Data Synthesis and Analysis

For quantitative synthesis, we converted diverse resilience outcomes into a common metric the standardized mean difference (Hedges' g) to enable meaningful comparison across studies. This process involved several stages to ensure construct validity and transparency.

Step 1: Establishing Construct Validity

To justify synthesizing different resilience indicators (e.g., crop yield, risk perception scores, household income), we first established that they measure related dimensions of adaptive capacity or reduced vulnerability. Drawing from the IPCC's framing of resilience [20], we categorized outcomes into three domains: (a) adaptive capacity (e.g., knowledge gains, livelihood diversity), (b) transformative capacity (e.g., institutional change, agency), and (c) reduced sensitivity (e.g., avoided losses, yield stability). Studies were only included in the same meta-analysis if their outcomes mapped onto at least one of these domains and were theoretically linked to enhanced resilience. Sensitivity analyses were planned to test whether findings differed across these domains.

Step 2: Extraction and Transformation of Effect Sizes

For each study, we extracted data to calculate effect sizes:

- For continuous outcomes (e.g., changes in yield, risk scores, income): We computed Hedges' "g" using the formula:

$$g = \frac{X^{-1} - X^{-2}}{\text{SDpooled}} \times J$$

  where X^{-1} and X^{-2} are the means of the intervention and comparison groups, SDpooled is the pooled standard deviation, and J is a correction factor for small sample bias.

$$J = 1 - \frac{3}{4df - 1}$$

- For binary outcomes (e.g., adoption success, household adoption): We calculated log odds ratios and converted them to Hedges' "g" using the formula $g = \ln(OR) \times \frac{\sqrt{3}}{\pi}$, following standard meta-analytic procedures [30].
- For pre-post designs without a control group: We calculated the standardized mean change using the formula:

$$g = \frac{\overline{X}_{post} - \overline{X}_{pre}}{SD_{pre} \times \sqrt{2(1-r)}} \times J$$

  where r is the pre-post correlation. We imputed a conservative correlation of r = 0.65 based on guidance from Gröndal (1993) [31] and conducted sensitivity analyses testing r = 0.5 and r = 0.8 to ensure robustness.

Step 3: Worked Example of Standardization

To illustrate, consider a study evaluating a climate-smart agriculture intervention reporting two outcomes:

- Yield increase (continuous): Mean difference = 0.5 t/ha, pooled SD = 0.8, sample size n = 50.

$$g = (0.5/0.8) \times J = 0.625 \times 0.99 = 0.62.$$

- Adoption rate (binary): 60% adoption in intervention vs. 30% in control, OR = 3.5.

$$\text{Converted g} = \ln(3.5) \times 0.55 = 1.25 \times 0.55 = 0.69.$$

Both effect sizes were then pooled within the study to create a single composite effect size, weighted by the inverse of their variance, ensuring each study contributed one independent effect to the overall meta-analysis. This composite approach prevented double-counting and maintained statistical independence.

Step 4: Weighting and Pooling

All effect sizes were weighted by the inverse of their variance to give greater precision to larger, more reliable studies. A random-effects model using the DerSimonian-Laird estimator was employed due to anticipated heterogeneity across study contexts and designs. Heterogeneity was quantified using the I^2 statistic, with values above 75% considered high and explored through subgroup analyses and meta-regression.

Step 5: Sensitivity Analyses

To test the robustness of our standardization approach, we conducted sensitivity analyses by:

- Comparing results using fixed-effects vs. random-effects models.
- Excluding studies with imputed pre-post correlations.
- Analyzing outcomes separately by resilience domain (adaptive capacity, transformative capacity, reduced sensitivity).

These analyses confirmed that the overall findings were not driven by methodological decisions in the standardization process.

Step 6: Handling of Dependent Effect Sizes

In 23% of the included studies (n = 96), authors reported multiple effect sizes from the same sample, for example, separate outcomes for different resilience domains or effect sizes at multiple post-intervention time points [20,27]. To avoid violating the independence assumption of meta-analysis, we employed a three-level random-effects meta-analytic model that explicitly partitions variance into three levels: sampling variance (Level 1), within-study variance (Level 2), and between-study variance (Level 3) [13,27]. This approach retains all available data while accounting for statistical dependencies. We compared the three-level results with a more conservative approach that aggregated multiple effect sizes per study into a single composite effect size. The results from both approaches were nearly identical (correlation of study-level pooled effects r = 0.96), indicating that our findings are robust to different methods of handling dependent effect sizes [27]. For simplicity and consistency with the broader meta-analysis literature [13], we report results from the composite effect size approach in the main text, with the three-level results available from the corresponding author upon request.

4. Results

4.1. Study Characteristics

The 418 included studies spanned 78 countries. The literature was heavily concentrated in the Global South (68%), particularly Asia (42%) and Africa (26%). Critical regions like Small Island States (4%) and the Arctic (1%) were underrepresented. Agriculture was the dominant sector (52%), followed by water management (24%), urban/coastal adaptation (18%), and health (6%).

In terms of study design, 34% (n = 142) were quasi-experimental (e.g., difference-in-differences, propensity score matching), 28% (n = 117) were pre-post comparisons without control groups, 22% (n = 92) were cross-sectional surveys with comparison groups, and 16% (n = 67) were randomized controlled trials or clustered RCTs [27]. The proportion of RCTs was highest in agricultural innovations (24% of agricultural studies) and lowest in governance innovations (3% of institutional studies), reflecting the inherent challenges of randomizing institutional reforms [17,18]. Mixed-methods designs accounted for 41% of all studies, with qualitative components typically providing critical contextual information that informed our coding of moderators [26,32]. Publication year trends showed exponential growth: only 8% of studies were published before 2015, 31% between 2015 and 2019, and 61% between 2020 and 2023 [3,8]. This temporal distribution indicates that the evidence base for adaptation innovations is recent and rapidly expanding, underscoring the timeliness of our synthesis [13].

4.2. Effectiveness of Innovation Types

The random-effects meta-analysis showed significant variation in effectiveness across innovation types. Institutional innovations were associated with the largest pooled effect size (Hedges' g = 1.24, 95% CI [1.07–1.41]), particularly those involving adaptive governance. Standalone technological solutions showed the smallest pooled effect (g = 0.71, 95% CI [0.52–0.90]). This pattern aligns with earlier typological work on adaptation interventions [33]. Notably, hybrid innovations (e.g., institutional-behavioral) outperformed single-domain approaches by a statistically significant margin (39%, $p < 0.001$) with effect sizes of g = 1.24 versus g = 0.71.

Among technological innovations, community-based early warning systems demonstrated particular promise in flood-prone regions [34], while digital agriculture tools showed variable adoption rates depending on user engagement [35]. Renewable energy adaptations, including solar-powered irrigation, contributed to resilience but required complementary institutional support [23].

Cost-effectiveness analysis (**Table 1**) revealed that EbA innovations delivered resilience at the lowest cost ($127 per unit, 95% CI [$89–$165]), with mangrove restoration and other nature-based solutions [36] proving particularly efficient. Technological solutions were the most expensive ($412 per unit, 95% CI [$301–$523]).

Table 1. Pooled Effect Sizes and Cost-Effectiveness by Innovation Type.

Innovation Type	Pooled Hedges' g [95% CI]	Cost per Resilience Unit (USD) [95% CI]*
Technological	0.71 [0.52, 0.90]	412 [301,523]
Institutional	1.24 [1.07, 1.41]	288 [201,375]
Behavioral	1.05 [0.88, 1.22]	154 [112,196]
Ecosystem-based (EbA)	1.16 [0.98, 1.34]	127 [89,165]

Note: * Unit defined as per hectare of agricultural land.

We further examined whether the superiority of hybrid over single-domain innovations held across different geographic and socioeconomic contexts [4,22]. Subgroup analyses revealed that the hybrid advantage was largest in Sub-Saharan Africa (g difference = 0.67, $p = 0.002$) and South Asia (g difference = 0.58, $p = 0.007$), regions characterized by weak institutional capacity and high multi-hazard exposure [2,3]. In contrast, in high-income countries (primarily studies from Australia, Southern Europe, and North America), the advantage of hybrid over single-domain approaches was smaller and not statistically significant (g difference = 0.18, $p = 0.31$) [1]. This pattern suggests that the added value of combining institutional and behavioral components is greatest in contexts where existing governance systems are least able to support technological rollouts [4,11]. Additionally, we tested for differences by hazard type: hybrid innovations outperformed single-domain approaches more strongly in drought adaptation (g difference = 0.61, $p = 0.004$) than in flood adaptation (g difference = 0.29, $p = 0.09$), possibly because drought requires coordinated water allocation decisions across multiple sectors and scales [18,20], whereas flood adaptation can sometimes succeed with localized structural measures alone [19,34]. These contextual nuances have important implications for tailoring innovation portfolios to specific risk profiles [7,15].

4.3. Contextual Moderators of Success

Meta-regression revealed that contextual factors are powerful moderators of innovation success (**Table 2**). Governance quality was the strongest positive predictor ($\beta = 0.68$, $p < 0.001$). The integration of Indigenous knowledge ($\beta = 0.52$, $p = 0.003$) and gender inclusion (≥40% women's participation, $\beta = 0.49$, $p = 0.008$) were also highly significant. In contrast, hazard severity had a negative association with success ($\beta = -0.31$, $p = 0.02$).

Table 2. Meta-Regression Results for Contextual Moderators.

Moderator	Coefficient (β)	SE	*p*-Value	95% CI
Governance Quality	0.68	0.12	<0.001	[0.45, 0.91]
Indigenous Knowledge	0.52	0.17	0.003	[0.19, 0.85]
Gender Inclusion (≥40%)	0.49	0.18	0.008	[0.14, 0.84]
Hazard Severity	−0.31	0.13	0.02	[−0.56, −0.06]
GDP per capita ($1k)	0.22	0.09	0.01	[0.05, 0.39]

Threshold analysis identified critical tipping points. Institutional innovations were significantly less likely to succeed in contexts with a GDP per capita below $2,500 (OR = 0.24, $p = 0.01$). For technological innovations, equitable distribution of benefits was only observed in projects with documented women's participation exceeding 40%.

To further unpack the governance quality finding, we decomposed the composite governance index into its six constituent World Bank Governance Indicators (voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption). Meta-regression with each component entered separately (controlling for GDP per capita and hazard severity) showed that government effectiveness (β = 0.51, $p = 0.001$) and rule of law (β = 0.44, $p = 0.003$) were the strongest individual predictors, whereas political stability was not significantly associated with innovation success (β = 0.12, $p = 0.34$) [11,25]. This decomposition suggests that the quality of day-to-day public administration and contract enforcement matters more for adaptation innovation than the absence of political violence or coup risk [17,18]. Practically, this implies that adaptation investments should prioritize strengthening civil service capacity and judicial institutions, not merely supporting stable governments [3,4]. Additionally, we examined interaction effects between moderators. The positive effect of women's participation on equity outcomes was amplified when combined with Indigenous knowledge integration (interaction term β = 0.37, $p = 0.02$), suggesting synergistic benefits from inclusive, pluralistic knowledge systems [22,37]. Conversely, the negative effect of hazard severity was exacerbated in low-governance settings (interaction β = −0.29, $p = 0.04$), indicating that climate shocks disproportionately undermine innovation success where institutional buffers are weakest [11,19].

4.4. Equity and Maladaptation Risks

Synthesis of studies reporting disaggregated data revealed significant equity concerns. Across 73% of technological innovation studies, evidence of elite capture was found, where the wealthiest quintile of the population received, on average, 68% of the benefits. This was calculated by comparing benefit incidence across income quintiles. Furthermore, 22% of agricultural innovations were coded as having a high risk of maladaptation. For example, crops that are both drought-resistant but require high water inputs during specific growth stages (e.g., maize hybrids, certain rice varieties) in semi-arid regions were found to exacerbate groundwater depletion [38], a finding derived from studies reporting negative long-term environmental or social feedbacks. Coastal adaptation projects similarly showed uneven benefit distribution without explicit equity provisions [39].

To examine whether maladaptation risk varied systematically by innovation type and geographic context, we conducted a logistic regression with maladaptation (coded present/absent) as the dependent variable [12,15]. After controlling for study quality and duration, ecosystem-based innovations had the lowest maladaptation risk (adjusted OR = 0.12, 95% CI [0.04–0.33], $p < 0.001$), whereas technological innovations had the highest (OR = 1.0 reference) [5,36]. Institutional innovations showed intermediate risk (OR = 0.54, 95% CI [0.29–1.01], $p = 0.053$), suggesting that governance reforms can reduce but not eliminate maladaptive outcomes [12,19]. Geographic patterns were striking: maladaptation was reported in 34% of studies from arid and semi-arid regions (primarily related to groundwater depletion and soil salinization), compared with 12% of studies from humid tropical regions [15,38]. This regional disparity likely reflects the tighter resource constraints and lower buffering capacity of dryland systems [3,20]. Importantly, studies that explicitly incorporated participatory scenario planning or future-oriented vulnerability assessments had 67% lower odds of maladaptation (OR = 0.33, 95% CI [0.16–0.68]), providing quantitative evidence for the value of anticipatory methods [19,26].

4.5. Publication Bias and Heterogeneity

Egger's test was significant ($p = 0.002$), indicating the presence of publication bias. A trim-and-fill adjustment imputed missing studies, reducing the overall pooled effect size by 18%, suggesting that the published literature overestimates true effects. Overall heterogeneity was high ($I^2 = 83\%$). Subgroup analysis by innovation type and UN subregion substantially reduced heterogeneity (to $I^2 = 41\%$), confirming that these factors explain a large portion of the variation in study findings.

We conducted additional publication bias analyses stratified by innovation type to determine whether bias differed across domains [27]. Egger's test was significant for technological innovations ($p = 0.003$) and behavioral innovations ($p = 0.02$) but not for institutional ($p = 0.19$) or ecosystem-based ($p = 0.31$) innovations [13]. The trim-and-fill adjustment reduced effect sizes most for technological innovations (from g = 0.71 to g = 0.53, a 25%

reduction) and least for EbA (from g = 1.16 to g = 1.08, a 7% reduction) [27,36]. This pattern suggests that studies of technological solutions often funded by the private sector or technology-focused donors are more susceptible to selective reporting of positive results [35,40], whereas EbA studies, frequently conducted by conservation organizations with less publication pressure, may present a more balanced evidence base [36,41]. To further assess small-study effects, we performed Egger's test separately for studies with sample sizes below and above the median ($n < 120$ vs. $n \geq 120$). Among technological innovations, small studies reported systematically larger effect sizes (mean g = 0.89) than large studies (mean g = 0.57, $p = 0.006$), consistent with publication bias [27,35]. No such small-study effect was observed for institutional or EbA innovations. These findings caution against over-reliance on small-scale pilot studies of technological interventions when making scaling decisions [4,15].

5. Discussion

This meta-analysis provides a comprehensive, quantitative synthesis of evidence on climate adaptation innovations, revealing a significant disconnect between research and practice. Our findings strongly support the integrated conceptual framework (**Figure 1**), demonstrating that innovation success is not inherent to the technology or practice itself but is profoundly shaped by the governance, social, and economic context in which it is embedded.

5.1. The Primacy of Hybrid, Context-Sensitive Approaches

Our results challenge a purely technocentric view of adaptation. The finding that hybrid institutional-behavioral innovations significantly outperform technological ones (g = 1.24 vs. 0.71, a difference of 0.53 in Hedges' g) aligns with Termeer et al. (2017) [4], who argue that transformational adaptation requires institutional flexibility and community engagement, not just new hardware. This suggests that the "adaptation deficit" is as much a governance deficit as a technological one. The superior cost-effectiveness of EbA ($127/unit) over technological solutions ($412/unit), despite its chronic underfunding, highlights a critical policy failure driven by a political preference for visible, short-term infrastructure over long-term, systemic ecological investments [41]. Broader and more participatory approaches to technology assessment, as advocated by Ely et al. [42], could help rebalance these priorities. Furthermore, behavioral innovations that shift mindsets and social norms show particular promise when combined with institutional reforms [43].

One unexpected finding was that the performance gap between hybrid and single-domain innovations widened over time [22]. In studies with follow-up periods exceeding five years, hybrid innovations maintained or increased their effectiveness advantage (g difference = 0.61 at year 1 vs. 0.79 at year 5+), whereas the effect of standalone technological interventions decayed significantly (g = 0.81 at year 1 vs. 0.48 at year 5+, $p = 0.01$) [1,15]. This temporal pattern suggests that technologies may lose their effectiveness due to maintenance failures, changing hazard regimes, or user attrition [35,40], whereas hybrid approaches build adaptive capacity that persists beyond the initial intervention period [22]. From a policy perspective, this finding argues for longer-term funding cycles (10+ years) that support iterative learning and institutional embedding rather than short-term project-based financing for hardware alone [3,44]. It also underscores the importance of monitoring and evaluation frameworks that track outcomes over decadal timescales [15], even though such long-term studies remain rare in the current evidence base [8,12].

5.2. The Critical Role of Contextual Thresholds

The meta-regression results provide empirical weight to theoretical claims about context-dependence. The strong positive association of governance quality ($\beta = 0.68$) with success supports Ostrom's [17] emphasis on institutional design and the value of polycentric approaches [24,25]. The identification of a GDP per capita threshold of $2,500 for institutional innovations quantifies the resource base necessary for complex governance reforms. Below this level, direct capacity building and financial support are prerequisites, as institutional barriers can otherwise prove insurmountable [11]. Similarly, the finding that ≥40% women's participation is a predictor of equitable technological outcomes provides a concrete, measurable target, moving Chu et al.'s [5] concept of an "equity-efficiency nexus" from theory to practice. Building transformative capacity at multiple scales, as described by Ziervogel [22], appears essential for navigating these thresholds.

Our threshold analysis also revealed that the relationship between GDP per capita and innovation success is not linear but rather exhibits a "poverty trap" dynamic [3,11]. Below the $2,500 threshold, the odds of institutional innovation success were 0.24, but between $2,500 and $5,000, odds increased to 0.89 (not significantly different from 1.0), and above $5,000, odds were 1.8 ($p$ = 0.01) [2,4]. This suggests that very low-income countries face qualitatively different constraints, perhaps related to the absence of basic state functions or extreme patronage networks that are not simply milder versions of constraints faced by lower-middle-income countries [11,19]. For policymakers, this implies that a one-size-fits-all approach to adaptation finance is inappropriate [3,25]. In the poorest contexts, international support may need to focus on foundational governance capacity (e.g., civil service training, anti-corruption courts, public financial management systems) before expecting that sophisticated institutional innovations (e.g., climate-risk insurance, water trading schemes) can succeed [18,44]. This finding aligns with recent calls for "climate-sensitive state-building" as an adaptation strategy in fragile and conflict-affected states [4,12].

5.3. Unpacking Equity and Maladaptation

The high prevalence of elite capture in technological interventions (73%) and the significant risk of maladaptation (22%) underscore the dangers of innovation pursued without a justice lens. This empirically supports the critiques of Eriksen et al. [12] and Tschakert et al. [14] that adaptation interventions can inadvertently reinforce existing inequalities or create new vulnerabilities. The integration of Indigenous knowledge systems, as documented by Boillat and Berkes [32], offers one pathway toward more equitable outcomes, aligning with our finding that such integration significantly predicts success (β = 0.52). Gender-transformative approaches that move beyond tokenistic inclusion are similarly critical [37].

The Kenyan County Climate Change Funds (CCCFs), which decentralized finance and mandated community representation, offer a powerful counter-example of institutional design [44]. By embedding procedural justice (who decides), they improved distributive justice (who benefits). This contrasts sharply with large-scale infrastructure projects that can create new forms of vulnerability [19] and the Senegal solar pump case, where a lack of gender-sensitive design increased women's labor, a classic example of maladaptation [45]. Democratizing the design and governance of adaptation technologies, as proposed by Nath [40], represents a crucial step toward more just outcomes. The concept of multispecies justice further expands the moral community to include ecosystems and non-human species [14].

We further explored whether elite capture could be predicted by project design features [5,12]. Among technological innovations, projects that were designed and implemented by external actors without local partner organizations were 3.2 times more likely to exhibit elite capture (95% CI [1.7–6.0]) compared with projects co-designed with local civil society or community-based organizations [37,40]. Similarly, projects with <20% of the budget managed locally had 4.1 times higher odds of elite capture [39,44]. These effect sizes are substantial and actionable: they suggest that relatively simple procedural reforms mandating local partnerships and decentralized budget management could dramatically reduce inequitable outcomes [26,29]. However, we note a caveat: co-design alone is insufficient if power asymmetries within communities are not addressed [14,19]. In several studies where co-design occurred but local elites dominated the consultation process, elite capture persisted [5,12]. This finding highlights the need for deliberate attention to intra-community power relations, including facilitated processes that amplify marginalized voices (e.g., women, lower castes, pastoralists) rather than assuming that any local participation automatically yields equitable outcomes [14,37].

To examine whether maladaptation risk varied systematically by innovation type and geographic context, we conducted a logistic regression with maladaptation (coded present/absent) as the dependent variable [12,15]. After controlling for study quality and duration, ecosystem-based innovations had the lowest maladaptation risk (adjusted OR = 0.12, 95% CI [0.04–0.33], p < 0.001), whereas technological innovations had the highest (OR = 1.0 reference) [6,7]. Institutional innovations showed intermediate risk (OR = 0.54, 95% CI [0.29–1.01], p = 0.053), suggesting that governance reforms can reduce but not eliminate maladaptive outcomes [12,19]. Geographic patterns were striking: maladaptation was reported in 34% of studies from arid and semi-arid regions (primarily related to groundwater depletion and soil salinization), compared with 12% of studies from humid tropical regions [15,38]. This regional disparity likely reflects the tighter resource constraints and lower buffering capacity of dryland systems [3,20]. Importantly, studies that explicitly incorporated participatory scenario planning or future-oriented vulnerability assessments had 67% lower odds of maladaptation (OR = 0.33, 95% CI [0.16–0.68]), providing quantitative evidence for the value of anticipatory methods [19,26].

5.4. Publication Bias and Its Implications

Egger's test was significant ($p = 0.002$), indicating publication bias. A trim-and-fill adjustment for missing studies reduced the overall pooled effect size by 18%, suggesting that the published literature overestimates true effects. Overall heterogeneity was high ($I^2 = 83\%$). Subgroup analysis by innovation type and UN subregion substantially reduced heterogeneity (to $I^2 = 41\%$), confirming that these factors explain a large portion of the variation in study findings.

We conducted additional publication bias analyses stratified by innovation type to determine whether bias differed across domains [27]. Egger's test was significant for technological innovations ($p = 0.003$) and behavioral innovations ($p = 0.02$) but not for institutional ($p = 0.19$) or ecosystem-based ($p = 0.31$) innovations [13]. The trim-and-fill adjustment reduced effect sizes most for technological innovations (from g = 0.71 to g = 0.53, a 25% reduction) and least for EbA (from g = 1.16 to g = 1.08, a 7% reduction) [27,36]. This pattern suggests that studies of technological solutions—often funded by the private sector or technology-focused donors—are more susceptible to selective reporting of positive results [35,40], whereas EbA studies, frequently conducted by conservation organizations with less publication pressure, may present a more balanced evidence base [36,41]. To further assess small-study effects, we performed Egger's test separately for studies with sample sizes below and above the median ($n < 120$ vs. $n \geq 120$). Among technological innovations, small studies reported systematically larger effect sizes (mean g = 0.89) than large studies (mean g = 0.57, $p = 0.006$), consistent with publication bias [27,35]. No such small-study effect was observed for institutional or EbA innovations. These findings caution against over-reliance on small-scale pilot studies of technological interventions when making scaling decisions [4,15].

5.5. Barriers to Implementation and Practical Pathways

Implementing the recommendations derived from our findings will meet real-world challenges [3,25]. First, political economic constraints: elite capture is not an oversight but a purposeful tactic for powerful players to preserve advantage [12,14]. Equity-weighted financing will consequently face resistance. To circumvent this, donors should employ a portfolio approach earmarking a portion (e.g., 30%) of adaptation funds exclusively for participatory, pro-poor innovations, thereby establishing a protected area for equity-focused experimentation [5,29].

Second, capacity constraints: many low-income nations lack the technical ability to create or operate hybrid adaptation initiatives [4,11]. Here, south-south cooperation and regional centers of excellence might give technical help without the conditionality commonly associated with northern donors [2,3]. Third, data limitations: real-time adaptation dashboards require monitoring systems that many local governments lack [28,39]. Low-cost, low-tech options such as community scorecards, participatory photography, or voice-based reporting via basic mobile phones can give meaningful equity measures without expensive infrastructure [32,37].

Fourth, institutional fragmentation: adaptation encompasses numerous ministries (agricultural, water, disaster, finance), and innovation broker authorities may fail to work across silos [18,25]. Mandating inter-ministerial committees with explicit decision rights and dedicated funding, rather than consultative responsibilities, can alleviate this fragmentation [4,44]. Fifth, evaluation timelines: donors often want outcomes within 2–3-year project cycles, whereas hybrid and EbA innovations sometimes require longer durations to demonstrate advantages [15,36]. Shifting to programmatic (rather than project-based) funding with 10-year timeframes, accompanied by intermediate process indicators (e.g., institutional capacity milestones), might align assessment incentives with the temporal realities of systemic change [3,22].

Acknowledging these limitations is not an excuse for inaction but a beginning point for realistic, context-sensitive implementation solutions [12,15]. **Table 3** synthesizes the minimal criteria for important equity and process metrics that adaptation dashboards should follow to ensure accountability and justice in innovation implementation

Table 3. Adaptation Innovation Dashboards Tracking, 2025.

Metric	Minimum Threshold
Women's participation	≥40%
Indigenous knowledge integration	≥50% of design phases
Cost-benefit equity ratio	≤1.5 (wealthiest: poorest)

Source: Researchers' data.

5.6. Theoretical Contributions

This study extends theory by empirically testing an integrated framework that synthesizes diffusion, governance, and transition theories. The strong moderating effects of governance quality, social inclusion, and economic thresholds provide quantitative support for Ostrom's [17] Institutional Analysis and Development framework, demonstrating that rules-in-use and community attributes are not peripheral considerations but central determinants of innovation outcomes. Our findings also provide empirical weight to Geels' [21] Multi-Level Perspective, as the differential performance of innovations across governance contexts indicates how socio-technical regimes support or hinder niche innovations.

Furthermore, we provide quantitative evidence for the "justice-centered adaptation" paradigm [5], demonstrating that procedural and recognitive justice measured through women's participation and Indigenous knowledge integration are not merely ethical add-ons but are empirically linked to better outcomes ($\beta = 0.49$ and 0.52, respectively). This contradicts the persisting belief in some policy circles that equitable considerations come at the expense of efficiency. Our results suggest the opposite: disregarding equality leads to elite capture, maladaptation, and eventually, diminished efficacy. The findings further underscore the relevance of anticipatory governance techniques that proactively design adaptation pathways [46], as indicated by the lower maladaptation risk linked with participatory scenario planning.

Our conceptual framework's emphasis on feedback loops and multi-scalar interactions receives indirect support from the temporal patterns we observed: hybrid innovations maintained effectiveness over time while technological ones decayed, suggesting that positive feedbacks (e.g., institutional learning, trust-building) may sustain hybrid approaches. However, direct examination of feedback mechanisms requires longitudinal data that remain sparse in the present evidence base. We therefore propose our framework as a generative hypothesis for future research rather than a completely validated model.

5.7. Comparison with Previous Meta-Analyses

Our findings both validate and extend earlier syntheses. Berrang-Ford et al. [8], in their global stocktake of adaptation evidence, identified a prevalence of technical and agricultural interventions but did not quantitatively evaluate effectiveness across innovation categories. Our meta-analysis presents the first rigorous, quantitative assessment of innovation typologies, highlighting the advantages of hybrid and institutional approaches. Similarly, Chausson et al. [36] established the success of nature-based solutions but did not systematically compare EbA with other innovation categories or examine contextual factors. Our cost-effectiveness analysis (EbA at $127/unit vs. technology at $412/unit) corroborates their findings while adding a comparison dimension. Lesnikowski et al. [9] assessed national-level adaptation efforts and identified governance as a major driver, but their research was limited to national policies rather than applied innovations. Our meta-regression quantifies the governance effect at the project level ($\beta = 0.68$), offering a more granular understanding. Finally, our equity findings extend the qualitative critiques of Eriksen et al. [12] and Tschakert et al. [14] by providing quantitative estimates of elite capture prevalence (73% in technological innovations) and maladaptation risk (22% overall), as well as identifying specific design features (local partnerships, decentralized budgeting) that reduce inequitable outcomes.

5.8. Limitations

This study has several limitations. The 18% reduction in effect size after publication bias correction suggests our pooled results may still be optimistic. High residual heterogeneity, while explained, confirms the high variability inherent in socio-ecological systems. Geographic biases persist, with SIDS and the Arctic critically underrepresented, limiting the generalizability of findings to these unique contexts. Furthermore, the short time frame of most primary studies (<5 years) precludes robust analysis of long-term maladaptive outcomes, a gap noted by Wise et al. [15].

Additional limitations warrant mention [13,27]. First, our reliance on peer-reviewed English-language literature likely underrepresents innovations documented in grey literature, technical reports, or non-English sources, potentially biasing our findings toward better-resourced and more internationally connected research teams [8,10]. While our supplemental search of preprint servers partially addressed this limitation, we cannot rule out linguistic or indexing biases [27]. Second, the PROGRESS-Plus framework, while comprehensive, does not fully capture intersectional vulnerabilities (e.g., the compounded marginalization of elderly Indigenous women with disabilities) [14, 29]. Future equity-focused syntheses should explore intersectional coding frameworks [5, 26]. Third, the cost-effectiveness data reported in primary studies varied widely in their accounting scope: some included only direct implementation costs, whereas others included opportunity costs, transaction costs, or environmental externalities [28, 36]. This heterogeneity likely increased the variance around our cost estimates and may have introduced systematic bias if studies with broader cost accounting systematically reported higher or lower costs per unit [41]. Fourth, our analysis could not account for the role of leadership individual champions or political entrepreneurs—who qualitative case studies suggest are often critical for innovation success [18, 22]. Fifth, the cross-sectional nature of most primary studies means that our findings on temporal dynamics (e.g., effect decay) rely on comparisons across studies with different follow-up lengths rather than within-study longitudinal data, introducing potential confounding by study cohort [1,15]. Despite these limitations, the consistency of our findings across multiple sensitivity analyses and the large sample size provides confidence in the main conclusions [13,27]. We have been transparent about methodological choices and have tested the robustness of our results through various sensitivity analyses, including alternative methods for handling dependent effect sizes, different approaches to publication bias correction, and subgroup analyses by study design and geographic region.

5.9. Implications for Policy and Practice

Our results hold several direct implications for adaptation policy and practice. First, the demonstrated superiority of hybrid approaches advocates for integrated programming that integrates institutional improvements, behavioral modification, and technical support, rather than walled treatments. Donors and governments should fund cross-sectoral programs that purposefully stimulate interaction among innovation types, with special focus on governance improvement in low-income environments.

Second, the determination of contextual thresholds gives practical assistance for targeting. In nations with GDP per capita below $2,500, adaptation expenditures should focus on basic governance capabilities before adopting complicated institutional innovations. Similarly, the 40% requirement for women's participation offers a clear, measurable aim for project design and monitoring. Funders should require gender-disaggregated data and enforce participation quotas as criteria for disbursement.

Third, the high prevalence of elite capture and maladaptation risk demands systemic reforms in how adaptation initiatives are developed, conducted, and evaluated. Co-design with local groups, decentralized budget management, and participatory scenario planning are not optional add-ons but vital defenses against inequitable and maladaptive results. We urge that financing agreements contain clawback clauses that allow recovery of monies if elite capture is identified, generating financial incentives for accountability.

Fourth, the publication bias findings suggest that policymakers and practitioners should regard small-scale pilot studies of technological advances with caution, particularly when making scaling decisions. Larger-scale, longer-term evaluations are needed to measure real-world effectiveness, and meta-analytic syntheses like ours should be routinely consulted to contextualize individual study findings.

Fifth, we propose three concrete institutional mechanisms to operationalize these insights: (1) Innovation Broker Authorities (IBAs) with mandates to foster cross-sectoral integration and enforce co-design quotas; (2) equity-weighted financing models that prioritize innovations based on composite scores multiplying effectiveness by PROGRESS-Plus equity indices; and (3) adaptation dashboards tracking key equity and process metrics in real-time, including women's participation, Indigenous knowledge integration, and cost-benefit equity ratios.

5.10. Future Research Priorities

Several big knowledge gaps appear from our synthesis. First, Arctic and SIDS innovation channels are notably underrepresented (<5% of research), despite these regions bearing disproportionate climate impacts [37]. Priority should be given to collaborative, decolonizing research with Inuit and Pacific populations that respects Indigenous knowledge ontologies and sovereignty.

Second, long-term maladaptation traps remain poorly known, as only 12% of research explore innovations beyond five years. Priority should be given to cohort studies tracking projects from 2010 onward, measuring effects over decadal timescales, such as Ethiopia's irrigation salinization instances [34]. Such investigations are crucial for detecting delayed adverse impacts that may not be visible in short-term evaluations

Third, digital gap justice requires urgent attention as AI and digital tools become more common in adaptation [43]. PROGRESS-Plus should be expanded to clearly address technology access, digital literacy, and data protection, ensuring that new achievements do not worsen existing imbalances.

Fourth, the micro-foundations of behavioral innovation remain underexplored [1]. Although our meta-analysis showed that behavioral interventions are beneficial on average (g = 1.05), we discovered substantial unexplained variance (I^2 = 67% among behavioral studies) that likely reflects heterogeneity in the psychological and social systems triggered [1,17]. For example, behavioral innovations based on social norms (e.g., community commitments to water conservation) may act through different channels than those based on economic incentives (e.g., subsidies for drought-resistant seeds) [3,4]. Few primary studies in our sample assessed mediating pathways (e.g., self-efficacy, trust, risk perception) or reported sufficient data for mediation meta-analysis [1, 19]. Future primary research should include theory-driven process assessments that examine psychological and social mediators, enabling future syntheses to discover which active elements promote behavioral change [1,33].

Fifth, scaling dynamics are critically understudied: only 9% of research collected systematic data on what happened when innovations were shifted from pilot to regional or national scale [14, 45]. Among those that did, scaling was associated with a 31% average decline in effect size (95% CI [8%–54%]), a phenomenon commonly called "scale-up penalty" [2,11]. Understanding whether this penalty is inevitable or may be avoided through adaptive scaling techniques (e.g., polycentric governance, modular design) is an urgent problem for implementation science [28,29].

Sixth, we highlight some intriguing methodological breakthroughs for alleviating research shortages. Blockchain-based benefit monitoring could improve transparency and encourage equal resource distribution. Real-time elite capture detection technology could find and resolve power imbalances as they develop. Agent-based simulations linked with Q-methodology for scalability modeling could assist anticipate policy sequencing success. Transdisciplinary integration strategies that leverage Indigenous knowledge ontologies are anticipated to reduce maladaptation in EbA efforts by 50%. These actions accord with certain equity indicators meant to make systems fairer and more inclusive (**Table 4**).

Table 4. Emerging Solutions for Research and Practice Gaps.

Gap	Solution	Expected Impact
Equity Metrics	Blockchain-benefit tracking	Real-time elite capture detection
Scalability Modeling	Agent-based simulations + Q-methodology	Predict policy sequencing success
Transdisciplinary Integration	Indigenous knowledge ontologies	50% ↓ maladaptation in EbA

5.11. Synthesis and Concluding Remarks on the Discussion

In combining our findings, numerous broad trends emerge. First, adaptation innovation is fundamentally a socio-technical process, not a solely technological one. The most effective innovations are those that jointly address governance frameworks, behavioral norms, and technical elements. Second, context is not only a backdrop but a crucial factor of performance, with observable thresholds that can guide targeting and sequencing of expenditures. Third, equity and effectiveness are not trade-offs but are scientifically linked: inclusive, justice-oriented techniques provide better outcomes and lower maladaptation risk. Fourth, the evidence base itself is affected by systematic biases, publication bias, geographic bias, and temporal bias that must be closely evaluated when translating research into policy.

These tendencies collectively advocate for a fundamental reorientation of adaptation practice: from project-based, technology-centric, short-term interventions to programmatic, hybrid, justice-centered, long-term investments in adapting capacity. The goal is not only to innovate but to innovate properly, with careful regard to who benefits, who chooses, and who suffers the risks. Our meta-analysis provides quantitative data to assist this reorientation, but the final test will be whether policymakers, funders, and practitioners embrace the implications of our results and translate them into persistent, equitable action on the ground.

6. Conclusions

This meta-analysis provides the first comprehensive quantitative synthesis of evidence on climate adaptation innovations, synthesizing 418 studies across 78 countries to reveal that innovation success is not inherent to any particular technology or practice but is profoundly shaped by governance, social inclusion, and institutional context. Our data reveal that hybrid approaches combining institutional and behavioral components considerably outperform technology solutions ($g = 1.24$ vs. 0.71), with EbA innovations proving most cost-effective ($127/unit) yet severely underfunded. Contextual thresholds GDP below $2,500 (OR = 0.24) and women's engagement below 40% predict innovation failure, but Indigenous knowledge integration ($\beta = 0.52$) and gender inclusion ($\beta = 0.49$) considerably boost equity and effectiveness. The significant incidence of elite capture (73%) and maladaptation (22%) highlights that neglecting justice leads to suboptimal and negative results. Publication bias adjustment lowered pooled impact estimates by 18%, with technological breakthroughs showing the biggest overstatement (25%), cautioning against over-reliance on small-scale pilots for scaling decisions. These findings reframe adaptation as a socio-technical governance challenge needing polycentric, justice-driven frameworks that include institutional reform, behavioral transformation, and ecological solutions. By providing quantitative evidence that equality and effectiveness are complementary rather than opposing objectives, this study presents a rigorous evidence framework for changing adaptation from incremental change to systemic, equitable resilience building. Future research must prioritize underrepresented regions (Arctic, SIDS), long-term evaluations (>5 years), behavioral mechanisms, and scaling dynamics to address crucial knowledge gaps and guide evidence-informed policy.

Author Contributions

A.W.W. conceptualized the study, developed the protocol, conducted the literature search, performed data extraction and statistical analysis, and drafted the manuscript. W.A.D. contributed to methodological refinement, data validation, interpretation of findings, and critical revision of the manuscript. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study is a meta-analysis of previously published studies and does not involve primary data collection from human participants or animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data analyzed during this study are derived from previously published peer-reviewed articles. The extracted dataset, coding framework, and statistical analysis scripts used for the meta-analysis are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare that they have no competing interests, financial or non-financial, that could have influenced the work reported in this manuscript.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

Appendix A. Detailed Search Strings

Used in Scopus, Web of Science, and ProQuest (January 2010–December 2023).

Core Syntax:

(TITLE-ABS-KEY("climate change adaptation" OR "climate resilience" OR "adaptive capacity") AND (TITLE-ABS-KEY("innovation" OR "technology" OR "ecosystem-based adaptation" OR "institutional change" OR "behavioral change") AND (TITLE-ABS-KEY("effectiveness" OR "evaluation" OR "barrier" OR "scalability" OR "replication")) NOT (TITLE-ABS-KEY("mitigation" OR "CO2" OR "emission reduction")).

Table A1. Database-Specific Modifications.

Database	Modification
Scopus	PUBYEAR > 2009 AND (LANGUAGE(English))
Web of Science	TS = () AND PY = (2010–2023) Indexes = SCI-EXPANDED
ProQuest	NOFT() AND pd(>2010-01-01) AND peer(yes)

Appendix B. Codebook for Data Extraction

"Piloted on 50 studies; Krippendorff's α = 0.84".

Table A2. Codebook Variables, Definitions, and Response Options.

Variable Category	Variable	Definition	Response Options/Units
Study Metadata	**Study ID**	**Unique Identifier**	**Numeric**
	Publication Year	Year of publication	2010–2023
	Country/Region	Implementation location	ISO 3166 codes
Innovation Traits	Primary Type	Dominant innovation domain	1 = Tech, 2 = Institutional, 3 = Behavioral, 4 = EbA
	Hybridization	Secondary innovation type	As above + 0 = None
	Development Mode	Origin of innovation design	1 = Endogenous, 2 = Exogenous
Effectiveness	Risk Reduction SMD	Standardized mean difference in key risks	Hedge's "g" [95% CI]
	Cost-Benefit Ratio	USD per unit resilience gain	Continuous
	Adoption Rate	% target population adopting	0–100%
Equity Dimensions	PROGRESS-Plus Coverage	# of equity criteria addressed	0–8 (Place, Race, Occupation, Gender, Religion, Education, SES, Social Capital)
	Benefit Distribution Gini	Inequality in benefit allocation	0–1 scale (0 = perfect equality)
Context	Governance Quality Index	World Bank Governance Indicators (avg.)	−2.5 to 2.5
	Indigenous Knowledge Depth	Integration level of local knowledge systems	0 = None

Appendix C. Quality Assessment Criteria

"NASA Tool for Climate Adaptation (2021), 9-point scale".

Table A3. Scoring Rubric.

Domain	Score 0	Score 1	Score 2	Score 3
Internal Validity	No control group/comparison	Pre/post comparison only	Quasi-experimental design	RCT or matched controls
Context Transparency	No site vulnerability details	Basic hazard description	Detailed socio-ecological data	Systems analysis with feedbacks
Equity Reporting	No PROGRESS-Plus variables	1–3 variables mentioned	4–6 variables analyzed	7–8 variables with disaggregation

Thresholds:

- High Quality: 7–9 points (Included in meta-regression).
- Medium Quality: 4–6 points (Included in descriptive synthesis only).
- Low Quality: 0–3 points (Excluded).

Table A4. Operational Examples.

Study Example	Internal Validity	Context	Equity	Total	Decision
RCT of drought-resistant seeds	3	2	3	8	Include
Case study of seawall project	1	2	1	4	Descriptive only
Policy analysis without field data	0	1	0	1	Excluded

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