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Advances in Management and Intelligent Technologies

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Cytomegalovirus Infection in Population Samples: Are Whole-Blood Levels of Cadmium, Mercury, Selenium, and Manganese Associated With CMV Serostatus?

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Abstract: Past experimental evidence links heavy metal exposure with immune function, but population-level associations with chronic viral infections remain unclear. We analyzed data on 554 U.S. participants (72% CMV-seropositive) to evaluate whether whole-blood levels of four metal, cadmium (Cd), mercury (Hg), selenium (Se), and manganese (Mn), were associated with cytomegalovirus (CMV) serostatus. We fit unadjusted logistic regression models for each metal, conducted a Weighted Quantile Sum (WQS) mixture analysis, performed a mediation assessment for systemic inflammation (high-sensitivity C-reactive protein, hs-CRP), and ran sensitivity analyses (trimming outliers, excluding participants with hs-CRP >10 mg/L, and arranging by hs-CRP levels). The four blood metals had minimal inter-correlation ($|\rho| \leq 0.07$). In unadjusted models, higher concentrations of Cd, Hg, and Mn were associated with lower odds of CMV seropositivity (odds ratios [ORs] < 1), whereas Se showed a positive but non-significant association (OR > 1). After excluding individuals with hs-CRP >10 mg/L (n=538), the inverse associations strengthened for Cd (OR ~0.63, 95% confidence interval [CI] 0.45–0.90), Hg (~0.68, 95% CI 0.53–0.88), and Mn (~0.49, 95% CI 0.27–0.91), while Se remained null (OR ~1.20, 95% CI 0.24–6.03). WQS mixture analysis identified Se as the top contributor (~77% weight) to the overall metal mixture effect, followed by Mn (~16%). Mediation by hs-CRP was negligible. In this exploratory, unadjusted analysis, higher blood levels of Cd, Hg, and Mn were less likely to be CMV-positive, but this might be due to other factors not accounted for. More research is needed using better-adjusted models before drawing firm conclusions.

Keywords: Cytomegalovirus (CMV); CMV Serostatus; Heavy Metals; Chronic Viral Infection; NHANES

Published: Feb 24, 2026

DOI: <https://doi.org/10.62177/amit.v2i1.1094>

1. Introduction

Cytomegalovirus (CMV) is a herpesvirus that results in lifelong latent infection and can cause age-related immunity and inflammation^[2]. Chronic CMV infection has been noted in immunosenescence and elevated cardiometabolic risk in older adults. Environmental heavy metals, on the other hand, are known to influence oxidative stress and immune function, with some toxic metals even potentially suppressing immunity and essential trace elements supporting it. Cadmium (Cd) and mercury (Hg) are non-essential toxic metals that can impair immune responses^[3] while selenium (Se) and manganese (Mn) are micronutrients that are involved in antioxidant defenses and enzymatic processes important for immune health^[4]. Prior research has suggested that heavy metal exposures could alter the susceptibility to infections. A recent study by Zhang et

al.^[8] found that a higher combined exposure to multiple heavy metals was associated with increased odds of persistent viral infections in humans. In that analysis, the overall heavy metal combinations had a positive association with CMV seropositivity (odds ratio ≈ 1.58) after multivariable adjustment with cadmium in particular, showing independent positive association with CMV infection risk. However, population-level evidence is still limited and sometimes inconsistent with whether specific blood metal concentration levels correlate directly with having CMV infection.

The present study aims to assess whether whole-blood concentrations of Cd, Hg, Se, and Mn are associated with CMV infection status in a population-based sample. We additionally explored whether systemic inflammation, which is measured by high-sensitivity C-reactive protein (hs-CRP), correlates or mediates these associations. By examining individual metals as well as their combined effect (as a mixture), this study seeks to find potential links between common blood metals and CMV serostatus.

2. Methods

2.1 Study Population

We analyzed cross-sectional data on 554 adult participants drawn from NHANES 2017 to 2018 population survey with biospecimens. All individuals had CMV serology, circulating hs-CRP, and whole-blood heavy metal measurements available. CMV serostatus (positive vs. negative) was determined by serum IgG antibody testing. Participants with any missing relevant data were excluded, yielding a final analytic sample of $n \approx 554$ (approximately 72% CMV-seropositive). The CMV-positive group tended to be older and of lower socioeconomic status, consistent with known CMV epidemiology (although demographic variables were not explicitly adjusted in our main analysis).

2.2 Exposure Measures

Whole blood levels of four heavy metals Cd, Hg, Se, and Mn were the primary exposures. These were measured by standardized laboratory methods (NHANES protocols)^[1] and reported in units of $\mu\text{g/L}$ (for Hg, Se, Mn) or $\mu\text{g/dL}$ (for Cd). We focused on these four metals because blood lead had 0% availability in the dataset and was thus excluded. For analysis, metal concentrations were log-transformed to reduce right-skewness and stabilize variance. We examined metals both individually and in combination.

2.3 Statistical Analysis

We first described the distribution of each metal by CMV serostatus. Summary statistics (medians, interquartile ranges) for the CMV-negative vs. CMV-positive groups were calculated, and we assessed pairwise Spearman correlations among the metals. The inter-metal correlations were low ($|\rho| \sim 0.01\text{--}0.07$), indicating minimal collinearity between these exposures.

For inferential analysis, we performed univariate logistic regressions to estimate the association between each metal and odds of CMV seropositivity. Each model treated CMV seropositive (CMV+) as the outcome and one metal (continuous log-scale) as the predictor, without additional covariate adjustment. We then employed a mixture modeling technique, Weighted Quantile Sum (WQS) regression, to assess the combined effect of the four-metal mixture on CMV status. The WQS method creates an index of the metal mixture (based on quantiles of each metal) and estimates its association with the outcome, while also providing weights that indicate each metal's relative contribution to any observed mixture effect. We specified the direction of the WQS index to reflect an increasing risk (to test whether higher metal mixture tends to increase odds of CMV positivity, consistent with prior literature). The WQS model yields an overall odds ratio for the metal mixture and weights summing to 1.0 for the components.

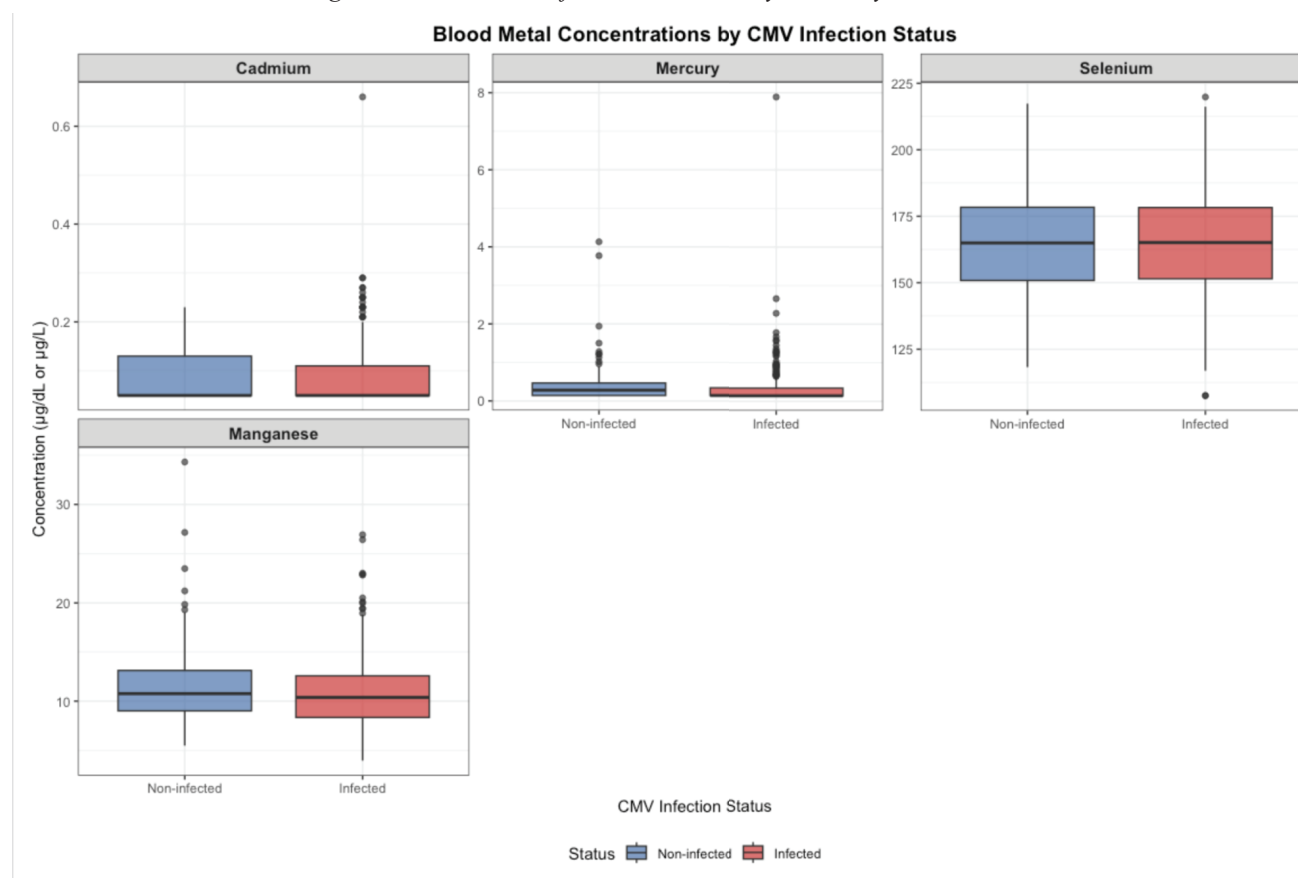
Several sensitivity analyses were conducted to test the robustness of results. (1) Influence of outliers: We trimmed extreme high values of each metal (approximately top 1%) and refit the logistic models on the trimmed sample ($n \approx 538$). (2) Excluding acute inflammation: We repeated analyses after excluding participants with $\text{hs-CRP} > 10 \text{ mg/L}$ ($n = 538$), since very high CRP suggests acute infection or inflammation that might confound or modify the CMV–metal relationship. (3) Stratification by inflammation level: We stratified the sample into low, moderate, and high hs-CRP groups (<1 , $1\text{--}3$, $>3 \text{ mg/L}$) to see if metal–CMV associations differed by baseline inflammation status. All analyses were performed using R (version 4.2) with two-sided significance tests and $\alpha = 0.05$.

3. Results

3.1 Descriptive Findings

Among 554 participants, 71.8% were CMV-seropositive. Median blood metal concentrations were on the same order of magnitude between CMV-positive and CMV-negative groups, with some small differences. For example, median Cd was ~ 0.05 $\mu\text{g/dL}$ in both groups; median Hg was slightly lower in CMV+ (0.14 $\mu\text{g/L}$) vs. CMV– (0.28 $\mu\text{g/L}$); It was ~ 165 $\mu\text{g/L}$ in both groups; and Mn median was somewhat lower in CMV+ (10.9 $\mu\text{g/L}$) vs. CMV– (11.7 $\mu\text{g/L}$). Metals showed right-skewed distributions with a few high outliers (especially for Hg and Mn), reinforcing the use of log-transforms and the need for the sensitivity check excluding outliers.

Figure 1: Distribution of whole-blood heavy metals by CMV serostatus



In Figure 1, each panel is a boxplot of metal concentration (log scale) in CMV-negative (CMV–) vs. CMV-positive (CMV+) individuals. The central line is the median and the box spans the interquartile range; whiskers and points indicate broader spread and outliers. Overall, CMV-seropositive individuals tended to have lower levels of Hg and Mn compared to CMV-seronegatives (note the lower median lines for Hg and Mn in CMV+ group), while Se levels were virtually similar between groups and Cd showed only a slight decrease in the CMV+ group. These distributional differences (lower Hg/Mn in the CMV+ group) are in a direction opposite to what might be expected if toxic metal exposure predisposed to infection. This initial observation hinted that any association might be confounded or subtle.

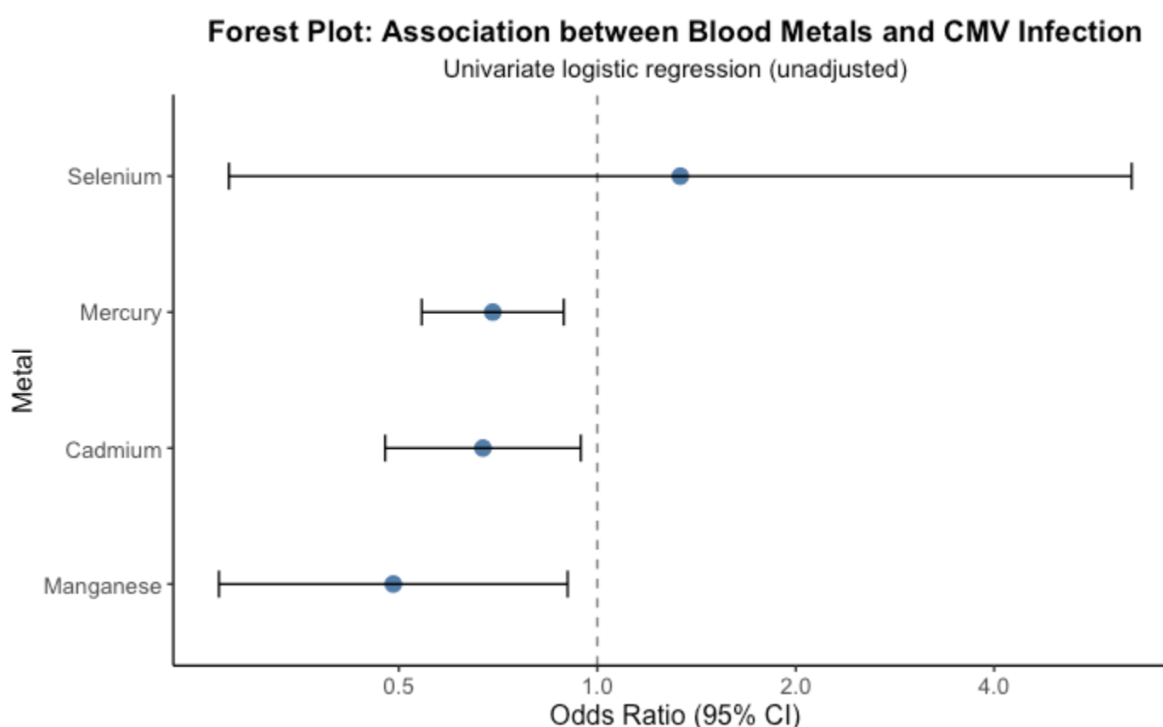
3.2 Individual Metal Associations

In unadjusted logistic regressions, higher blood levels of Cd, Hg, and Mn were all associated with lower odds of being CMV-seropositive (odds ratios [OR] below 1.0), whereas Se showed an OR above 1.0 (suggesting higher Se linked to higher odds of CMV positivity). However, none of these associations reached statistical significance in the full sample, and confidence intervals were wide (all intervals included the null value of 1). For example, in the initial models, the OR for Cd (per unit increase on the log-scale) was around 0.8 (95% confidence interval (CI) spanning ~ 0.5 – 1.2), Hg OR ~ 0.9 (CI ~ 0.7 – 1.1), Mn OR ~ 0.7 (CI ~ 0.4 – 1.1), and Se OR ~ 1.1 (CI ~ 0.4 – 3.0), none showing a clear effect. We observed that the direction of association for Cd, Hg, and Mn was consistently inverse (OR < 1), meaning individuals with higher levels of these metals

tended to have lower prevalence of CMV, whereas Se's point estimate was >1 . Given that CMV seropositivity is strongly age-dependent and our models did not adjust for age or other covariates, these results were interpreted with caution.

When we excluded participants with hs-CRP > 10 mg/L (removing those with likely acute inflammation), the inverse associations became stronger and achieved statistical significance for three metals. In this restricted sample ($n = 538$), higher Cd was associated with significantly lower odds of CMV seropositivity (OR = 0.63, 95% CI: 0.45–0.90, $p = 0.011$), as were higher Hg (OR = 0.68, 95% CI: 0.53–0.88, $p = 0.003$) and higher Mn (OR = 0.49, 95% CI: 0.27–0.91, $p = 0.025$). Selenium in this analysis remained inconsistent (OR ≈ 1.20 , 95% CI very wide, $p = 0.83$). Thus, under conditions excluding acute inflammation, the data suggested that individuals with greater Cd, Hg, or Mn exposure had roughly 30–50% lower odds of past CMV infection than those with lower exposure, a counterintuitive finding. Trimming extreme metal values (to address outliers) attenuated these associations slightly (eg Cd OR ~ 0.57 , $p \sim 0.05$, no longer definitively significant), but the overall inverse trends remained.

Figure 2: Odds ratios (95% CI) for CMV seropositivity associated with each blood metal (unadjusted logistic regression).



In Figure 2, the plot shows the estimated OR for being CMV-positive per unit increase in log-transformed metal concentration. An OR below 1 (dotted vertical line) indicates an inverse association (higher metal level linked to lower CMV odds). As shown, cadmium, mercury, and manganese each have ORs below 1.0, whereas selenium's OR is above 1.0. Error bars (95% CI) for all metals cross the null line, indicating no significant association in the primary unadjusted model. In a sensitivity analysis excluding individuals with very high CRP (not depicted in this figure), the ORs for Cd, Hg, and Mn shifted further below 1 and became statistically significant, consistent with a stronger inverse relationship in the low-inflammation subset.

3.3 Metal Mixture Analysis

Using WQS regression, we assessed the four metals as a mixture to see if a combined exposure burden related to CMV serostatus. In the WQS model (constrained to identify a positive overall association, ie testing if higher mixture increases CMV risk), the mixture index did not show a significant association with CMV (in fact, the direction of the estimated mixture effect was negative, although non-significant). Interestingly, the WQS algorithm assigned the majority of weight to selenium ($\sim 77\%$ of the total mixture effect weight). This indicates that Se was the most influential component of any potential mixture effect on CMV, even though Se alone did not show a clear positive association in univariate analysis. Manganese received the next largest weight ($\sim 16\%$), while Cd and Hg each had very small weights in the WQS mixture. The dominance of Se in

the weighted index suggests that any mixture effect — if present — might be driven largely by selenium's relationship with CMV. We also ran a WQS model allowing for a negative mixture direction (testing if higher metal levels collectively reduces CMV risk); in that exploratory run, the mixture effect was likewise non-significant, reinforcing that no strong linear mixture signal was detectable with this unadjusted approach. These mixture results, combined with very low inter-metal correlations, imply that each metal's association with CMV was essentially acting independently (and possibly in opposite directions), rather than a concerted mixture effect.

3.4 Mediation by Inflammation

We found no evidence that systemic inflammation (hs-CRP) mediated the association between metals and CMV serostatus. In our data, blood levels of Cd, Hg, Se, and Mn were not significantly correlated with hs-CRP (all Pearson r near 0, $p > 0.5$), and CMV seropositivity was only modestly associated with higher CRP (CMV+ had slightly higher median CRP than CMV–, but with substantial overlap). The formal mediation analysis yielded an extremely small indirect effect for each metal via hs-CRP, in the order of a risk ratio ~ 1.0003 (virtually no mediation) and a mediated proportion of around -0.1% (the negative value indicating no meaningful mediation). In short, adjusting for or accounting for hs-CRP did not change the metal–CMV associations, and the direct effects remained essentially the same. We also considered hs-CRP as an effect modifier: stratified results hinted that the inverse associations of Cd and Hg with CMV were strongest among individuals with low baseline inflammation ($\text{CRP} < 1 \text{ mg/L}$). For those with higher inflammation, the patterns were less consistent (and sample sizes were small), but no clear positive associations emerged in any stratum. This suggests the inverse relationships were not driven by an inflammatory pathway but could be more pronounced in healthy (low-inflammation) subpopulations.

4. Discussion

4.1 Principal Findings

In this cross-sectional analysis of ~ 550 adults, we observed that higher whole-blood levels of cadmium, mercury, and manganese were inversely associated with CMV seropositivity. In other words, participants with greater exposure to these toxic metals had a lower prevalence of past CMV infection. Selenium showed a positive but inconsistent association with CMV (higher Se with slightly higher CMV seroprevalence, but not statistically significant). These results run counter to the initial expectation that heavy metal exposure might suppress immune function and thereby increase the risk of chronic viral infections. Instead, our unadjusted findings suggest a scenario where individuals with more Cd, Hg, or Mn exposure were less likely to have contracted CMV. However, we suspect that this apparent protective association is not causal. The most plausible explanation is confounded by host factors: CMV infection is associated with demographic and lifestyle variables (age, socioeconomic status, living conditions, etc.), and those same variables can correlate inversely with certain metal exposures. For example, CMV seropositivity is higher in older adults, lower-income and urban populations, and those with larger families or crowding in childhood. Conversely, blood Hg and Se tend to be higher in people who eat more fish (often individuals of higher socioeconomic status or particular cultural diets), and Cd is higher in smokers and certain occupational groups. If, say, higher-income or health-conscious individuals have greater seafood intake (raising Hg and Se) but also lower CMV infection risk (due to different exposure history or healthcare access), an inverse association between Hg/Se and CMV would emerge. Without controlling for age, smoking, diet, socioeconomic status, and other confounders, the direction of association can be misleading. Our analysis did not adjust for these factors, so confounding is a likely driver of the unexpected inverse relationships.

Reverse causation is another consideration, chronic CMV infection might conceivably influence behavior or physiology in ways that affect metal levels (although this is less likely). For instance, if CMV-positive individuals had poorer health or dietary changes that resulted in lower accumulation of certain metals, that could create an association. We cannot rule out selection biases either – participants with missing data were excluded, and if those systematically differed, or if healthier individuals (less likely CMV+) had higher likelihood of having complete biomarker data, that could skew results.

Another possible factor is measurement and exposure timing. Whole blood metal levels reflect a mixture of recent and longer-term exposure, depending on the metal's kinetics. They may not perfectly capture lifetime exposure relevant to acquiring a persistent infection like CMV. Non-differential exposure misclassification (measurement error) would generally bias

associations toward null, but if it interacts with confounders, it could produce odd results. It's also notable that our WQS mixture analysis highlighted selenium – an essential element – as contributing the most to any mixture effect on CMV. Selenium's role in immunity is complex^[6]: adequate Se is necessary for optimal immune response, but very high Se or certain forms might not confer additional benefit. In our study, selenium did not show a clear protective or harmful trend for CMV, yet in the mixture context it dominated, possibly because the other metals were all trending inversely. This dominance of Se could indicate that the mixture's net effect was driven by an essential nutrient (Se) rather than the toxicants, hinting that our observed associations might relate to nutritional or dietary patterns (fish consumption, supplement use) more than to toxicological harm.

Our findings differ from those of Zhang et al.^[7], who reported positive associations between heavy metal exposure and persistent infections including CMV. In their nationally representative analysis with multivariate adjustment, higher urinary Cd was associated with higher odds of CMV seropositivity (adjusted OR ~1.43), and a heavy metal mixture (including lead and arsenic which we could not assess) increased CMV risk. The contrast with our unadjusted results reinforces that confounding and covariate adjustment can dramatically alter the direction of associations. It may be that after controlling for age, socioeconomic and nutritional factors, the true relationship between toxic metals and CMV is positive (as heavy metals may impair immune surveillance and vaccine responses). Indeed, toxicological studies support that lead and cadmium exposure can weaken immune defense, so it is expected that higher exposure correlates with greater infection susceptibility if all else is equal^[8]. In short, we interpret our results not as evidence that cadmium, mercury, or manganese protect against CMV, but as an indicator of confounded exposure patterns.

Despite these limitations, this study contributes some novel observations. To our knowledge, it is one of the first to examine whole-blood metal biomarkers in relation to CMV infection status in a general population sample^[5]. Most priority research on heavy metals and infection focused on clinical outcomes or vaccine response, not prevalent latent viral infections.

4.2 Strengths of this study include

This study has several strengths. First, it integrated biomonitoring data on four distinct metals together with CMV serological status in a relatively large population-based sample (>500 participants), enabling a broad assessment of metal exposure in relation to a common chronic infection. Second, we employed multiple complementary analytical approaches—simple univariate logistic models, a WQS mixture model (with conceptual extension to a Bayesian kernel machine regression), a mediation analysis, and various sensitivity checks—to ensure that the findings were examined from different methodological angles. These diverse methods bolster confidence that the observed patterns are not artifacts of a single analytical technique. Third, the very low inter-metal collinearity in this dataset simplified interpretation of results, as each metal's association with CMV could be evaluated with minimal concern for confounding by the other metals in the mixture.

4.3 Limitations to note

However, several limitations must be considered. Most importantly, our analyses included no adjustment for potential confounders such as age, sex, race/ethnicity, socioeconomic status, diet (e.g. seafood intake affecting Hg levels), smoking, kidney function, or supplement use. The absence of covariate adjustment means that the inverse associations we observed are likely biased by confounding; indeed, prior research using fully adjusted models has found that higher heavy metal exposure is associated with higher risk of persistent infections (for example, a mixture of heavy metals was linked to increased odds of CMV seropositivity, OR \approx 1.58). A related limitation is the cross-sectional design of this study, which precludes any determination of causality or temporal directionality between metal levels and CMV infection; we cannot infer whether metal exposure influences infection risk or if infection status (or correlated factors) influences metal levels. There is also the possibility of selection bias and outlier influence – the need to exclude participants with missing data may have introduced bias if those individuals differ systematically, and although we performed an outlier trimming sensitivity analysis, extreme values could still impact the unadjusted results. Additionally, the metal mixture analysis was incomplete due to missing lead data: lead is a major toxic metal, and its unavailability in our dataset narrows the scope of the mixture and may omit an important exposure. Finally, some subgroup analyses had limited precision; for instance, when arranging by inflammation status, the cell sizes in the high hs-CRP group were small, making those particular estimates unstable and less reliable.

5. Conclusion

In summary, this exploratory study of a population sample ($n \approx 554$, CMV seroprevalence $\sim 72\%$) found that higher blood cadmium, mercury, and manganese levels were associated with lower odds of CMV seropositivity, while selenium showed mixed, inconclusive patterns. Systemic inflammation (hs-CRP) did not mediate these relationships. These findings, contrary to toxicological expectations, are likely explained by confounding, for example, demographic and lifestyle factors that link lower CMV infection risk with higher heavy metal exposure surrogates, rather than any protective effect of toxic metals. Given the absence of adjustment for key covariates, no causal inferences can be made. Our results align with at least one prior fully adjusted study in highlighting selenium's importance in the heavy metal mixture and suggesting complex, element-specific effects. Overall, the data underscore that analyzes of environmental exposures and infections must carefully account for confounding variables. Future research should employ multivariable models or longitudinal designs to confirm whether toxic metal exposures truly increase susceptibility to persistent infections (as experimental evidence would suggest) and to clarify the role of essential elements like selenium in modulating infection risk. Until then, our findings should be interpreted cautiously. They serve as a hypothesis-generating insight into how lifestyle and exposure factors relate with infection outcomes, rather than evidence of a direct protective effect of heavy metals on CMV infection.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Editorial: Bridging Disciplines for the Sustainable Development Goals: Interdisciplinary Evidence, Methods, and Practice-Relevant Insights

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Abstract: Based on the six papers selected for the special issue from the 2025 Interdisciplinary Symposium on the Sustainable Development Goals (ISSDGs) (Auckland), this editorial paper reviews the interdisciplinary research findings and proposes a future research agenda. Although SDGs research is booming, existing literature still faces challenges such as disciplinary fragmentation and limited practical application. The interdisciplinary dialogue aims to promote substantive integration among fields such as economics, engineering, management, education, and digital technology. By summarizing the themes and comparing the methods of the selected papers, this paper recaps three aspects, including the measurement and governance mechanisms of sustainable performance, the trade-offs between environmental risks, industrial development, and infrastructure resilience, and human-centered digital transformation and innovation in sustainable education. Then, this paper proposes five research directions, including the causal pathways between SDG targets and policy integration design, a framework for the institutionalized measurement of governance capacity, data ethics and cross-scale comparability issues, the scaling and contextualized implementation of sustainable innovation, and the expansion and refinement of social sustainability indicator systems. Overall, this paper summarizes the findings of the Special Issue and provides insights into further theoretical development and practical application.

Keywords: Sustainable Development Goals; Interdisciplinary Integration; Sustainability Governance; Policy Implementation; Research Agenda

Published: Feb 25, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1108>

1. Introduction

The Sustainable Development Goals (SDGs) offer a comprehensive and integrated approach to addressing the world's most pressing challenges, such as climate change, environmental deterioration, social inequality, digital transformation, and sustainable economic development (Falk & Nemon, 2023). In contrast to the previous development agendas, the SDGs highlight the relationships between policy fields and sectors, thus pointing to the systemic character of sustainability challenges (Nilsson et al., 2018).

Although academic research related to the Sustainable Development Goals has grown significantly in recent years, a

considerable portion of the existing literature remains confined to a single disciplinary tradition or subject area (Kanie et al., 2019; Sianes et al., 2022). Many studies focus on specific goals, departments, or technical levels, with limited attention paid to cross-goal interactions, institutional interdependence, or governance mechanisms (Bennich et al., 2020). Furthermore, although many contributions have helped to illuminate important empirical discoveries or conceptual advances, relatively few have focused on the issue of transforming research results into the implications and implementation strategies necessary for practice (Berrone et al., 2023; Norström et al., 2020). Therefore, the integration of economic, technological, social, and institutional perspectives that are crucial for the effective implementation of the Sustainable Development Goals remains unevenly developed (Leal Filho et al., 2022).

This Special Issue is closely related to the 2025 Interdisciplinary Symposium on Sustainable Development Goals (ISSDGs) held at the University of Auckland on September 26, 2025. The symposium brought together researchers from economics, management, engineering, arts, and social sciences to discuss evidence-based and technology-driven approaches to sustainable development. The symposium provides a forum for interdisciplinary discussions, encouraging researchers to consider the potential of various analytical methods and perspectives and work together to achieve the Sustainable Development Goals in different institutional Settings. The ISSDGs Special Issue aims to consolidate selected research contributions that reflect both the diversity and the coherence of SDG-oriented interdisciplinary research. The six papers included address sustainability challenges at different levels, ranging from macro-level measurement frameworks and environmental governance to firm behavior, infrastructure resilience, education, and digital inclusion. Rather than focusing on a single goal or methodology, the Special Issue highlights how sustainability challenges can be better understood when economic, technological, social, and institutional dimensions are considered together.

2. Motivations and Objectives of the Special Issue

Although the introduction section outlines the broader academic and institutional background of this special issue, its motivation is more specifically oriented towards strengthening the analytical and practical basis of academic research on the Sustainable Development Goals. The interdisciplinary exchanges during the symposium highlighted a common understanding that although disciplinary specialization is indispensable, it is still insufficient to address the systematic and multi-scale nature of sustainable development challenges. What we need is well-designed research to integrate different viewpoints while focusing on governance conditions and implementation feasibility. Therefore, this special issue is guided by two closely related goals.

Firstly, it seeks to take interdisciplinary integration as a specific analytical direction rather than a rhetorical label. Here, interdisciplinarity refers to the structured combination of theoretical frameworks, empirical methods, and evaluation criteria in interdisciplinary fields to capture the interdependent relationships among economic, social, technological, and institutional processes.

Secondly, it emphasizes the relevance of governance and the transformation of practice. The outcome of sustainable development depends not only on analytical insights, but also on institutional capabilities, regulatory design and organizational incentives. This special issue aims to strengthen the connection between theory and practice, encouraging contributors to place their analysis in the context of actual decision-making and consider implementation methods.

In conclusion, these goals make this special issue not only a compilation of topics but also a well-considered effort aimed at promoting the methodological and practical maturity of interdisciplinary academic research on sustainable development goals.

3. Review and Selection Process

This Special Issue was planned in parallel with the Interdisciplinary Symposium on Achieving the Sustainable Development Goals in June 2025 and was launched through an open call for papers. Authors were invited to submit their full manuscripts during the paper solicitation stage rather than after the symposium to ensure there is sufficient time for rigorous peer review and revision before publication.

The review and selection process followed a multi-stage procedure, aiming to ensure academic quality, interdisciplinary

relevance, and consistency with the goals of the special issue.

First, all submitted manuscripts had undergone an initial editorial screening. At this stage, the invited editors evaluated the thematic relevance of the submissions to the interdisciplinary scope of the Sustainable Development Goals of this special issue and conducted originality checks to ensure compliance with academic integrity standards.

Second, submissions that passed the initial screening were evaluated according to a set of predefined review criteria outlined in the Special Issue's full-paper review guidelines. Relevance to the symposium topic and special issues, originality and contribution, methodological rationality, clarity and organization, analytical quality, utilization of pertinent literature, and academic writing standards are some of these requirements. These guidelines are always applicable to all materials that are submitted to facilitate an impartial and open evaluation procedure.

Third, manuscripts were subject to a double-blind peer-review process, supported by more than 20 reviewers with high-quality journal review or publication experience. At least two experts and academics in the related subject independently reviewed each submission. Achieving a balance in interdisciplinary evaluation was emphasized, making sure that submissions are assessed from the proper disciplinary perspective while also considering their overall contribution to research on the Sustainable Development Goals.

The invited editor made editorial decisions on revisions and acceptance based on the reviewers' reports and the special issue's overall goals. All accepted papers underwent two rounds of revision, enabling authors to respond to reviewers' feedback and further enhancing the overall quality and consistency of the papers.

After this rigorous selection process, the final rejection rate was 66%, and six papers were eventually accepted for the special issue. These contributions represent a carefully selected set of interdisciplinary research, reflecting the knowledge exchange promoted by the symposium and the journal's academic standards.

4. Thematic and Methodological Contributions

The thematic structure of this Special Issue reflects the interdisciplinary dialogue initiated during the Interdisciplinary Symposium on Achieving the Sustainable Development Goals. Rather than organizing contributions solely by discipline or SDG category, the papers are grouped according to shared research concerns that emerged through conference discussions, including measurement and governance of sustainability, management of environmental and infrastructural risks, and human-centered digital transformation. These themes capture both the diversity of approaches and the common questions that connected scholars across fields.

4.1 Measuring and Governing Sustainability Performance

One of the themes that can be identified from the Special Issue is related to the measurement and governance of sustainability performance. The studies included in this Special Issue critically discuss the shortcomings of the traditional economic measures and examine new approaches that are capable of addressing the environmental and social aspects of performance. At the macro-level, this focus is represented in the research on Green GDP accounting, which suggests the use of an entropy method to enhance comparability among G20 countries (Chen & Lin, 2026). Through the integration of the environmental dimension into national accounts, this research addresses the issue of applying sustainability-adjusted indicators for policy evaluation and development planning.

In addition to the macro-outlook, another advantage of the report is that it analyzes the sustainable development performance at the company level, with a focus on the relationship between executive education in China's real estate industry and corporate profitability (Wu et al., 2026). It was found that a higher level of executive education does not necessarily lead to better financial performance and that efficiency and context are more decisive. This finding was highly praised at the session on governance and management, where it was pointed out that human capital investment should be in line with organizational structure and the environment to ensure sustainable economic performance. Together, these two papers illustrate how sustainability governance requires coherent measurement frameworks and realistic assessments of organizational capabilities.

4.2 Environmental Trade-offs, Food Security, and Infrastructure Resilience

Another major topic emerging from the Special Issue concerned environmental trade-offs associated with industrial development and infrastructure expansion. Some of the discussions were centered on the conflict between economic

development, environmental sustainability, and resilience. This is evident in the paper that examines the effect of industrial air pollution on food security and relevant agricultural production in Eastern China (Lyu & Yang, 2026). By linking the data of industrial air pollution and economic variables in agriculture, the paper presents empirical evidence of spillovers between sectors, showing how industrial air pollution harms agriculture and food security. It is worth noting that the paper emphasizes the moderating effect of governance ability, indicating the agreement reached at the conference that environmental outcomes are determined not only by technology but also by governance ability.

From the perspective of engineering and infrastructure, the contribution of the improvement experience Fourier decomposition solves the sustainability problem through the perspectives of resilience and maintenance efficiency (Sun et al., 2026). A signal processing method for early damage identification of structural systems was proposed and experimentally verified. During the seminar, infrastructure resilience is often discussed as a practical entry point for sustainable development, especially in rapidly urbanizing areas. This article directly addresses this issue by providing an economically effective and technically robust approach, which can reduce resource waste and extend the service life of infrastructure. Taken together, these two studies underscore the importance of interdisciplinary approaches that connect environmental science, engineering, and governance in managing sustainability-related risks.

4.3 Human-Centered Digital Transformation and Sustainability Education

The third prominent subject under discussion in the special issue is the use of digital technology in creating an inclusive and sustainable society. The scholars not only concentrated on the efficiency of technology but also explored the social and ethical dimensions of digital change. This is seen in the research paper on intergenerational communication in the digital age, where the researchers examine the contribution of older content creators on short video-sharing platforms to the realization of digital inclusion and social sustainability. (Shen et al., 2026). Through content analysis and audience engagement, the authors of this paper illustrate the role of digital platforms in enhancing the presence and social engagement of older people, which corresponds to the discussions on inclusiveness and social well-being at the symposium.

Issues pertaining to the application of human-centered technology have also reinforced the role of artificial intelligence in sustainable early childhood education (Fan et al., 2025). This conceptual paper proposes an “artificial intelligence co-pilot” framework, which views artificial intelligence as a helper system in the role of teachers, rather than as a decision-maker. This framework reflects the discussions during the conference on balancing innovation with ethical boundaries and professional autonomy. By emphasizing value guidance, functional consistency and clear constraints, this study helps to discuss how emerging technologies can support sustainable education without compromising human judgment or teaching value.

4.4 Synthesis Across Themes

Although these six papers involve different empirical backgrounds and methodological approaches, the connections among them have become evident through conference-based communication. Some common insights have emerged in different themes. First of all, sustainability outcomes are formed by the interaction between technological solutions and governance structures. Second, the measurement and evaluation framework plays a crucial role in determining priorities and guiding actions. Thirdly, digital and technological innovation must be integrated into people-oriented and environmentally sensitive designs to support inclusive and sustainable progress towards achieving the Sustainable Development Goals.

Through the organization of special issues based on themes that mirror these shared concerns, the editorial underlines that these articles should not be seen as isolated research endeavors but rather as part of an ongoing interdisciplinary conversation that has been initiated at the conference and continued through this publication.

5. Future Research Directions

The contributions of this special issue and the interdisciplinary discussions initiated during the conference have pointed out several research directions worthy of continuous academic attention. These directions do not represent isolated gaps but rather reflect the structural challenges in current research on Sustainable Development Goals and highlight the opportunities where an interdisciplinary approach can generate the greatest added value.

5.1 SDG Interactions, Causal Pathways, and Integrated Policy Design

A recurring viewpoint in the paper is that the outcome of sustainable development is determined by the interaction among

policies, sectors, and goals, rather than by isolated interventions. Therefore, future research should go beyond single policy assessment and shift towards designing and evaluating comprehensive policy options to clearly simulate the interactions and causal pathways of the Sustainable Development (Allen et al., 2025). For instance, policies that focus on the achievement of industrial upgrading and economic growth may need complementary policies on environmental regulations and agricultural support in order to avoid negative spillover effects on food security. Similarly, only with the support of appropriate organizational reforms and governance mechanisms can policies oriented towards education and skills be transformed into sustainable productivity improvements. Developing an analytical framework capable of capturing these interactions remains a key task in interdisciplinary research on sustainable development goals (Pradhan et al., 2017).

5.2 Governance Capacity as a Determinant of Sustainable Development Outcomes

Some of the articles in this special issue strongly emphasize that governance capacity is not a background condition but a positive determinant of policy effectiveness. This point is an indication that future research must conceptualize and measure governance capabilities more explicitly (Khan & Hussain, 2024). Potential approaches include formulating operational indicators for regulatory enforcement, institutional transparency, public participation, and digital governance mechanisms (Breuer et al., 2023). Then, empirical research can examine how changes in governance capacity mitigate the impact of environmental, technological, and social interventions. This type of work will help explain why similar policies produce different results in different regional and institutional settings and will enhance the policy relevance of Sustainable Development Goals research (Knox & Orazgaliyev, 2024; Wiegant et al., 2024).

5.3 Data Quality, Comparability, and Ethical Data Infrastructures

Reliable measurement remains a core challenge in sustainable development research (Biermann et al., 2022). As demonstrated by the green GDP and corporate sustainability assessment work, the indicators related to the Sustainable Development goals rely on consistent, transparent, and comparable data across scales. Future research should explore how to better integrate the data generated by national accounting systems, corporate reporting frameworks, and platforms to support comprehensive sustainability analysis (Bebbington & Unerman, 2018; Sætra, 2023). Meanwhile, the increasing use of digital and AI-driven data sources has raised significant ethical issues (Camilleri, 2024). Issues such as consent, data protection, bias, and accountability must be addressed to ensure that data infrastructure supports rather than undermines trust and social legitimacy in sustainable governance (Taeiagh, 2025).

5.4 Scaling and Field Deployment of Sustainability-Oriented Innovations

Several studies in this Special Issue propose methods or frameworks that have been validated under controlled or pilot conditions. A key challenge for future research lies in scaling these innovations and assessing their performance in real-world settings (Cooley & Linn, n.d.). For instance, infrastructure monitoring technologies must be tested under conditions of environmental noise, operational complexity, and long-term use (Azimi et al., 2020). Similarly, community-based digital inclusion initiatives and AI-supported education models need to be evaluated in different demographic, cultural and institutional contexts (Fu et al., 2025). For transforming promising innovations into sustainable and scalable solutions, it is crucial to focus on research related to implementation, adaptation, and system-level integration (Adenle et al., 2023).

5.5 Human-Centered Sustainability and the Measurement of Social Outcomes

Finally, the special issue emphasizes the significance of a people-centered perspective in sustainable development research. Achievements such as well-being, social inclusion, professional autonomy, and dignity are often recognized but still not fully measured. Future studies should aim at creating strong interdisciplinary tools for the measurement of these “social sustainability” dimensions (Custodio et al., 2023; Li et al., 2025). A design with a mix of quantitative and qualitative elements could be especially useful for studying complex social outcomes like intergenerational unity, senior digital participation, and teachers’ experience with AI-based teaching. Strengthening the empirical basis of social sustainability indicators is crucial for ensuring that the progress of sustainable development goals is in line with human values and life experiences (Jansen et al., 2024).

6. Conclusion and Acknowledgments

This Special Issue demonstrates that interdisciplinary research can generate more than broad narratives about sustainability:

it can offer tangible approaches, mechanisms, and governance knowledge. The six papers together offer an advancement in SDG thoughts through better measurement (Green GDP), understanding capability routes (executive education and company performance), estimating inter-sector environmental spillovers (pollution and agriculture), justifying engineering innovations for resilience (enhanced EFD for damage detection), and suggesting human-focused digital approaches for inclusion and education (silver-haired influencers and AI co-pilot pedagogy).

We would like to express our sincere appreciation to all authors for their excellent work and active participation in the whole process of reviewing and revising. We also appreciate the efforts of the anonymous reviewers whose comments helped improve the quality of the published papers. Finally, we thank the editorial team of Advances in Management and Intelligent Technologies for their professional support and guidance in the development of this Special Issue. It is our hope that this collection will stimulate further interdisciplinary collaboration and inform future research, policy, and practice related to the Sustainable Development Goals.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Executive Education, Corporate Profitability, and the Sustainable Development Goals: Evidence from China's Real Estate Industry

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Abstract: This study investigates the interconnections among SDG 4 (Quality Education), SDG 8 (Decent Work and Economic Growth), and SDG 11 (Sustainable Cities and Communities) by examining the role of executive human capital in China's listed real estate firms. Using panel data from over 200 firms between 2018 and 2022, the study employs multivariate econometric models to analyze how the educational backgrounds of CEOs and CFOs influence corporate profitability, measured by ROA, ROE, and ROIC. The findings indicate that CEOs holding at least a bachelor's degree exhibit a weak positive association with asset-based profitability, while CFO education does not display a stable positive effect, possibly reflecting conservative financial strategies in a highly regulated industry. By contrast, asset turnover consistently emerges as a key determinant of firm performance. Overall, the results suggest that the economic impact of executive education is context-dependent and mediated by industry characteristics. The study provides micro-level evidence on how educational attainment translates into firm performance, contributing to the understanding of sustainable economic growth and urban development within the SDG framework.

Keywords: Sustainability; SDGs; Executive Education; Real Estate; Profitability; CEO; CFO; China

Published: Feb 25, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1109>

1. Introduction

To explore micro-level linkages among the Sustainable Development Goals (SDGs), this study empirically examines how the educational background of CEOs and CFOs in Chinese listed real estate firms—an outcome associated with SDG 4 (Quality Education)—influences corporate profitability, a core objective of SDG 8 (Decent Work and Economic Growth). The analysis is framed within the interrelated goals of SDG 4, SDG 8, and SDG 11 (Sustainable Cities and Communities), recognizing the central role of the real estate sector in urban development and economic sustainability. While investment in higher education is widely acknowledged as a driver of human capital accumulation and high-quality growth, how such human capital operates at the executive level to shape firm outcomes remains insufficiently understood, particularly in emerging and policy-sensitive markets.

Existing literature on executive education and firm performance provides mixed and often inconclusive evidence. Theoretical perspectives such as Upper Echelons Theory and Human Capital Theory suggest that executives' educational attainment may influence strategic decision-making and organizational outcomes (Hambrick & Mason, 1984). However, empirical

results vary across industries and institutional environments. In the context of China's real estate and construction sectors—characterized by high capital intensity, regulatory intervention, and cyclical fluctuations—the extent to which executive education translates into improved profitability is unclear. This study addresses this gap by systematically examining whether firms led by more highly educated CEOs and CFOs outperform their peers, while explicitly distinguishing between the roles and responsibilities of these two executive positions.

From a practical and policy perspective, this study provides insights for corporate boards, regulators, and executive recruitment committees concerned with leadership selection and governance effectiveness. Rather than treating education as a uniform signal of managerial quality, the analysis highlights the importance of aligning executive competencies with sector-specific operational and regulatory demands. Empirically, the study analyzes a panel of Chinese listed real estate firms using profitability indicators such as return on assets (ROA) and return on equity (ROE), positioning executive human capital as a mechanism linking quality education (SDG 4) to sustainable economic growth (SDG 8), with broader implications for advancing sustainable cities and communities (SDG 11).

2. Literature Review

2.1 Chinese Real Estate Industry and the SDGs

Since China's market-oriented reforms, the real estate industry has become a major pillar of economic growth. The separation of land ownership and land-use rights in the late 1980s enabled large-scale urban development and private sector participation (Fung et al., 2006). Real estate has contributed substantially to GDP, employment, and related industries, especially in major cities such as Shanghai and Beijing (Fung et al., 2006; Xu et al., 2021).

Rapid expansion, however, has generated structural challenges. Housing price inflation, speculative investment, and high price-to-income ratios have raised concerns about affordability and social stability, particularly for middle- and low-income households (Sheng et al., 2024). Regional disparities exacerbate these issues, as coastal areas experience faster growth and higher prices than inland regions, creating spatial inequality (Ren et al., 2014). Market overheating has also increased systemic financial risks, raising questions about long-term sustainability (Zhi et al., 2019).

These dynamics place the sector at the center of Sustainable Development Goals, especially SDG 11 (Sustainable Cities and Communities). Real estate firms influence housing supply, land-use efficiency, and urban form (Glaeser et al., 2017). Government interventions including purchase restrictions and land supply regulation aim to stabilize markets though effectiveness varies by region (Li et al., 2020; Ren et al., 2014). Beyond urban sustainability, investment in education and human capital (SDG 4) supports managerial capability and labor productivity, enhancing firm efficiency and economic growth (SDG 8). Improved performance may also stabilize employment and income distribution, addressing inequality (SDG 10) (Wang et al., 2015; Zhang et al., 2018).

2.2 Corporate Governance for SDGs

Corporate governance provides the framework for aligning strategic decision-making with financial and sustainability objectives. In real estate, governance mechanisms are critical. Upper Echelons Theory suggests that executives' cognitive bases and values, including education, shape organizational outcomes (Hambrick & Mason, 1984). Human capital theory highlights that education enhances analytical capacity and productivity, supporting firm performance (Becker, 1964).

Research shows that top management characteristics, including education, tenure, and functional background, influence innovation, competitiveness, and profitability (Bantel & Jackson, 1989; Carpenter, 2002; Aboramadan, 2021). In real estate, these attributes affect financing, project development, and regulatory compliance. While higher education generally strengthens strategic capability, its effect on profitability depends on industry context and practical experience (Wiersema & Bantel, 1992; Putra, 2021).

Board-level governance further shapes SDG outcomes. Educational diversity enhances cognitive diversity, decision quality, and firms' adaptability to regulatory and environmental changes (Boadi & Osarfo, 2019; Mukhibad et al., 2024). Well-educated executives and boards are better equipped to interpret sustainability regulations, improve disclosure, and integrate ESG considerations, supporting SDG 11 (Ho, 2005; Khatib et al., 2020).

Overall, while prior studies examine education, governance, and performance, limited attention has been paid to their

collective contribution to SDG outcomes in China's real estate industry. This study situates corporate governance and executive education within the SDG 4–8–10–11 framework.

3. Hypothesis development

Upper Echelons Theory suggests that executives' educational backgrounds shape their cognitive abilities and decision-making styles, thereby influencing firm outcomes (Hambrick & Mason, 1984). From a human capital perspective, higher education enhances analytical capacity and strategic judgment, which may improve corporate performance (Becker, 1964). Empirical evidence indicates that CEOs graduating from prestigious universities are often associated with higher managerial competence and leadership quality, although findings in China remain mixed due to institutional and industry-specific factors (Jalbert, Furumo, & Jalbert, 2010; Zhao & Liao, 2015). Accordingly, this study proposes the following hypothesis:

H1: CEO education has a positive impact on profitability in the Chinese real estate industry.

Chief Financial Officers (CFOs) play a central role in financial management, risk control, and investment decisions, making their educational background critical to firm performance. Human capital theory suggests that higher education equips CFOs with essential financial expertise and analytical skills, which can enhance financial reporting quality and governance effectiveness (Becker, 1964; Muttaqin & Kurnia, 2023). Firms therefore tend to favor CFOs with higher levels of education, particularly in capital-intensive and highly regulated industries such as real estate (Chahyadi & Abusalim, 2011). Based on these arguments, this study proposes the following hypothesis:

H2: CFO education has a positive impact on profitability the Chinese real estate industry.

4. Methodology

This study adopts a quantitative research methodology to examine the impact of CEO and CFO educational background on the profitability of Chinese real estate companies. The analysis is based on panel data collected from listed real estate firms over a number of years. The study follows the methodological framework used in Nguyen & Nguyen (2024) but adapted for the Chinese real estate industry and adjusted the time horizon to present diversity effects.

Table 1 below shows the variables in this study, including variable names, symbols, definitions, explanations, and information sources.

Table 1: Key variables identified as determinants of the performance of real estate and construction companies in previous literature and this study.

Panel A: Dependent variables			
Variable (Code)	Definition	Explanation	Source
Return on equity (ROE)	Net Income/Total Equity	Measures return on shareholders' equity; higher ROE indicates higher profitability.	Calculated from financial statements
Return on assets (ROA)	Net Income/Total Assets	Reflects asset profitability; higher ROA indicates more efficient asset use.	Calculated from financial statements
Return on Invested Capital (ROIC)	(Net profit + finance costs)/(Total assets - current liabilities + notes payable + short-term borrowings + long-term liabilities due within one year)	Measures return on all invested capital, reflecting core operating profitability.	Calculated from financial statements
Panel B: Independent variables			
Educational level of chief operations officer (EDUCEO)	Dummy variable = 1 if the CEO has a bachelor's degree or higher, otherwise = 0	Captures CEO's educational level.	Annual report
Education level of chief financial officer (EDUCFO)	Dummy variable = 1 if the CFO has a bachelor's degree or higher, otherwise = 0	Captures CFO's educational level.	Annual report
Panel C: Control variables			

Firm size (SIZE)	Natural logarithm of total assets	Indicates firm scale; larger firms often have operational advantages.	Financial statements / Annual report
Net working capital (NWC)	Current assets - Current liabilities	Measures liquidity and short-term financial health.	Financial statements / Annual report
Total assets turnover (TAT)	Total sales (or Total revenue)/Total assets	Reflects efficiency in using assets to generate revenue.	Financial statements / Annual report
Liquidity (LIQ)	Current assets/Current liabilities	Indicates ability to meet short-term obligations.	Financial statements / Annual report
Leverage (LEV)	Total debt/Total equity	Measures financial leverage; higher ratio implies more debt financing.	Financial statements / Annual report
Firm age (AGE)	Number of years of listing of the company	Reflects operational experience and maturity.	Financial statements / Annual report
Firm growth rate (FGR)	Total assets in year - assets in year (n-1) - Total / Total assets in year (n-1)	Measures annual growth rate of total assets.	Financial statements / Annual report

4.1 Data collection and sample selection

4.1.1 Sample size and periodicity

The sample consists of 141 publicly listed real estate companies in China observed over a five-year period from 2018 to 2022, yielding 3,007 firm-year observations that include multiple CEO and CFO appointments. Firms are selected based on the following criteria: (1) the firm is publicly listed; (2) it is classified as a real estate company according to the Exchange Classification Standard (K70); and (3) firms listed after 2018 or with substantial missing data are excluded. These criteria ensure data consistency and comparability across firms and time.

4.1.2 Data sources

Financial data was collected from audited financial reports, annual reports, and stock exchange disclosures published on CSMAR. Educational background of CEOs and CFOs from company annual reports and executive biographies on official company websites and links to annual statements. Macroeconomic indicators are based on GDP growth rates from China's National Bureau of Statistics and the World Bank, inflation rates, and benchmark interest rates.

4.1.3 Analytical methods

To investigate the relationship between executive education and firm profitability, this study adopts a dummy-variable approach that converts educational attainment into categorical indicators. CEO and CFO education levels are divided into two groups: high school or below and bachelor's degree or above. The latter is coded as 1, while high school or below serves as the baseline category and is omitted from the regression to avoid multicollinearity. This specification enables a direct comparison of firms led by executives with higher education while maintaining a unified sample.

It is acknowledged that this binary classification may obscure heterogeneity within higher education, such as postgraduate degrees, MBA qualifications, elite university backgrounds, or fields of study. However, due to data availability constraints and the need for consistency across firms and years, a dichotomous proxy is employed, and its limitations are explicitly considered in the interpretation of results.

The empirical model is specified as: $FP_{it} = \beta_0 + \beta_j IV_{it} + \gamma_k CV_{it} + \varepsilon_{it}$

Herein, FP_{it} represents firm financial performance measured by ROA, ROE, and ROIC; β_0 , β_j and IV_{it} includes the key independent variables EDUCEO and EDUCFO; γ_k is a vector of control variables; and finally, CV_{it} denotes the random error term of the model.

To enhance reliability, multiple estimation techniques are employed, including OLS, fixed-effects (FEM) and random-effects (REM) models selected using the Hausman test, generalized least squares (GLS) to correct for heteroskedasticity and autocorrelation, and generalized method of moments (GMM) to address potential endogeneity using lagged instruments.

4.2 Robustness tests

Several robustness checks are conducted to validate the empirical findings. Continuous variables are winsorized to reduce the influence of extreme values, and sub-sample analyses are performed by dividing firms into high- and low-leverage groups. The consistency of results across these specifications supports the robustness of the conclusions. Descriptive statistics (Table 2) further show that executive educational attainment in China's real estate sector is relatively low during the sample period, providing important context for evaluating the observed effects.

Table 2: The education level of the study sample.

Position	CEO		CFO	
	Frequency		Frequency	
	High school or below	Bachelor or above	High school or below	Bachelor or above
Year				
2018	340	213	65	34
2019	311	216	65	31
2020	310	224	68	30
2021	307	220	73	34
2022	295	209	66	30

5. Results and discussions

5.1 Descriptive statistics

Table 3 reports the descriptive statistics of the main variables used in the regression analysis. The mean value of ROE is slightly negative (-0.0003) with a standard deviation of 0.0294, indicating weak and, in some cases, negative profitability among sampled real estate firms during the study period. The average ROA and ROIC are also relatively low, at 0.0154 and 0.0232 respectively, reflecting modest returns in this capital-intensive sector. Net working capital and leverage exhibit extreme minimum and maximum values, suggesting substantial financial dispersion and the presence of outliers. Specifically, net working capital ranges from $-6.1\text{E}+10$ to $4.58\text{E}+11$, while leverage varies between -155.79 and 45.55 . Firm growth rates also show pronounced volatility, highlighting uneven performance across firms.

Table 3: Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
ROE	779	-0.0003	0.029356	-22.1201	0.4438
ROA	779	0.015417	0.001779	-0.593	0.1156
ROIC	344	0.023205	0.005739	-1.02552	0.23866
SIZE	779	23.9044	0.052663	19.68533	28.29301
AGE	354	28.91093	0.376117	12.08	69
NWC	779	2.07E+10	1.65E+09	-6.1E+10	4.58E+11
LIQ	779	2.019257	0.04071	0.116966	9.372211
LEV	779	3.098194	0.247672	-155.79	45.55322
TAT	779	0.023525	0.002083	-0.86747	0.162338
FGR	322	-1.49135	0.465447	-105.631	24.37816

5.2 Correlation matrix

Table 4 presents the correlation matrix for the model variables. The three profitability measures—ROE, ROA, and ROIC—are positively and significantly correlated, indicating internal consistency. ROIC shows a strong correlation with ROA ($r = 0.937$, $p < 0.01$) and a moderate correlation with ROE ($r = 0.223$, $p < 0.01$). Firm size is positively correlated with ROIC but shows weak or insignificant correlations with ROA and ROE, while net working capital is strongly related to firm size ($r = 0.652$, $p < 0.01$). Total asset turnover exhibits very strong correlations with ROA and ROIC, reflecting the importance of asset efficiency for profitability. Other variables, including liquidity, leverage, firm growth, and firm age, display relatively low correlations. Overall, the results indicate no serious multicollinearity concerns, though the high correlation between asset

turnover and ROA/ROIC warrants attention.

Table 4: Matrix of correlations.

Variable	ROE	ROA	ROIC	SIZE	AGE	NWC	TAT	LIQ	LVE	FGR
ROE	1.000									
ROA	0.285***	1.000								
ROIC	0.223***	0.937***	1.000							
SIZE	-0.030	-0.024	0.158***	1.000						
AGE	0.001	0.037	0.009	-0.003	1.000					
NWC	0.046	0.035	0.118***	0.652***	0.131***	1.000				
TAT	0.248***	0.956***	0.922***	-0.058	0.066*	0.019	1.000			
LIQ	0.058	0.150***	0.050	-0.389***	0.121***	-0.098***	0.188***	1.000		
LVE	0.109***	-0.093***	0.008	0.224***	0.007	0.051	0.101***	-0.156***	1.000	
FGR	0.130***	0.488***	0.493***	-0.049	-0.045	0.052	0.428	0.123***	-0.093***	1.000

***p < 0.01, **p < 0.05, *p < 0.1.

5.3 Multivariate regression analysis and GLS regression analysis

The regression analysis of the three profitability indicators—Return on Equity (ROE), Return on Assets (ROA), and Return on Invested Capital (ROIC)—using five different estimation techniques (Pooled OLS, FEM, REM, GLS, and GMM) provides comprehensive insights into the impact of CEO and CFO education levels, alongside traditional firm-level controls.

The regression results across these five models for the dependent variables ROE, ROA, and ROIC are presented in Tables 5-7.

Table 5: Regression results of the dependent variable ROE

	ROE				
	Pooled OLS	FEM	REM	GLS	GMM
AGE	-0.0059 (-0.5873)	-0.0581 (-0.9036)	-0.0023 (-0.2391)	-0.0059 (-0.587)	
FGR	0.0088 (0.9319)	0.0087 (0.7276)	0.01 (1.0584)	0.0088 (0.932)	0.0081* (1.7652)
NWC	2.212E-12 (1.4531)	-6.347E-13 (-0.1209)	6.167E-13 (0.5341)	2.212E-12 (1.453)	1.088e-12* (1.7317)
TAT	3.5381*** (2.944)	2.7598* (1.703)	3.272*** (2.7419)	3.5381*** (2.944)	3.5299 (1.3739)
LIQ	0.0003 (0.0038)	-0.0435 (-0.3521)	0.0524 (0.7329)	0.0003 (0.004)	0.0402 (0.8081)
LEV	0.0246*** (3.3903)	0.0282*** (3.0398)	0.0227*** (3.1556)	0.0246*** (3.39)	0.0209 (1.2141)
SIZE	-0.1173* (-1.7013)	-0.0748 (-0.1687)	-0.0086 (-0.6945)	-0.1173* (-1.701)	-0.0107 (-1.072)
EDUCEO	-0.1883 (-0.6626)	-1.3085* (-1.7051)	-0.1912 (-0.671)	-0.1883 (-0.663)	0.1816 (0.6491)
EDUCFO	0.2364 (1.188)	0.2126 (0.5184)	0.2282 (1.1444)	0.2364 (1.188)	-0.209 (-0.6812)
N	310	310	310	310	310
R2	0.0893	0.0867	0.0822	0.089	0.0675

T-statistics in parentheses.

*p < 0.1, **p < 0.05, ***p < 0.01.

Table 6: Regression results of the dependent variable ROA

	ROA				
	Pooled OLS	FEM	REM	GLS	GMM
AGE	-0.0001 (-0.709)	-0.0008 (-0.9869)	-3.00E-04 (-1.2302)	-0.0001 (-0.709)	
FGR	0.0008*** (5.0812)	0.0007*** (4.6268)	0.0008*** (5.4107)	0.0008*** (5.081)	0.0006 (1.19)
NWC	-3.395E-14 (-1.416)	2.473E-14 (0.3643)	-1.16E-14 (-0.4294)	-3.395E-14 (-1.416)	4.14E-14 (1.3276)
TAT	0.751*** (39.679)	0.6861*** (32.738)	0.7187*** (38.592)	0.751*** (39.679)	0.7783*** (13.051)
LIQ	-0.0037*** (-2.965)	-0.0083*** (-5.1903)	-0.0065*** (-4.9863)	-0.0037*** (-2.965)	-0.0059 (-1.1058)
LEV	0.0000759 (0.6633)	0.0001 (1.2036)	1.00E-04 (1.1324)	0.0000759 (0.663)	-0.0000216 (-0.1702)
SIZE	0.0029*** (2.695)	-0.0113** (-1.9768)	0.0006** (2.1149)	0.0029*** (2.695)	0.0003 (0.813)
EDUCEO	0.0075* (1.6716)	0.0249** (2.5085)	9.30E-03 (1.5726)	0.0075* (1.672)	0.0383 (1.5198)
EDUCFO	-0.0031 (-0.9876)	0.0057 (1.0738)	7.16E-05 (0.0186)	-0.0031 (-0.988)	-0.0389 (-1.4111)
N	310	310	310	310	310
R2	0.8839	0.8820	0.8778	0.884	0.8404

T-statistics in parentheses.

*p < 0.1, **p < 0.05, ***p < 0.01.

Table 7: Regression results of the dependent variable ROIC

	ROIC				
	Pooled OLS	FEM	REM	GLS	GMM
AGE	-0.0005** (-2.0332)	-0.0002 (-0.2072)	-0.0009** (-2.3612)	-0.0005** (-2.033)	
FGR	0.0014*** (6.3042)	0.0012*** (5.3902)	0.0012*** (6.1136)	0.0014*** (6.304)	0.0008 (0.7764)
NWC	-5.829E-14 (-1.6341)	-2.172E-14 (-0.233)	2.043E-14 (0.4765)	-5.829E-14 (-1.634)	1.535E-13 (1.3919)
TAT	1.2875*** (45.725)	1.2297*** (42.733)	1.2524*** (48.111)	1.2875*** (45.725)	1.373*** (9.1651)
LIQ	-0.0078*** (-4.2693)	-0.0024 (-1.1145)	-0.0062*** (-3.2857)	-0.0078*** (-4.269)	-0.0139*** (-2.8959)
LEV	0.0004** (2.0848)	0.0003* (1.8195)	0.0003** (2.2539)	0.0004** (2.085)	-0.0000306 (-0.0759)
SIZE	0.007*** (4.3235)	-0.0009 (-0.1092)	0.0015*** (3.109)	0.007*** (4.324)	0.0009*** (2.8872)
EDUCEO	0.0109 (1.6363)	0.0115 (0.8408)	0.0081 (0.9048)	0.0109 (1.636)	0.1153 (1.4129)
EDUCFO	-0.0056 (-1.2028)	0.0053 (0.7215)	0.0002 (0.0411)	-0.0056 (-1.203)	-0.1275 (-1.3562)
N	310	310	310	310	310
R-sq	0.9119	0.9248	0.9181	0.912	0.7330

T-statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The results for return on equity (ROE) indicate that CEO education (EDUCEO) is consistently associated with a negative coefficient across all estimation models, reaching marginal statistical significance only in the fixed-effects model (-1.3085 , $t = -1.7051$). Although weak, this negative association suggests that higher CEO educational attainment does not necessarily enhance equity-based profitability in China's real estate sector and may even exert a modest dampening effect. One possible explanation lies in the industry's strong exposure to regulatory intervention and cyclical fluctuations, where strategic adaptability, policy awareness, and market experience may be more influential than formal academic credentials.

In contrast, CFO education (EDUCFO) exhibits a more consistent negative relationship with firm profitability, showing statistically significant negative effects on both ROE and ROA across several model specifications. This finding suggests that higher educational attainment among CFOs may be associated with more conservative financial decision-making, which could constrain short-term profitability. In a volatile and policy-sensitive real estate environment, academically trained CFOs may prioritize risk control and regulatory compliance over aggressive capital deployment, potentially reducing equity and asset returns. Moreover, the emphasis on theoretical training in finance-related education may limit the practical effectiveness of financial strategies in complex market conditions.

Turning to the control variables, total asset turnover (TAT) emerges as a robust and positive determinant of ROE, ROA, and ROIC, underscoring the central role of asset utilization efficiency in driving profitability. Macroeconomic growth also positively influences firm performance, reflecting the importance of a supportive economic environment. Leverage displays mixed effects: it enhances capital-based returns while weakening asset-based profitability, highlighting the trade-off between financial amplification and balance-sheet risk. Firm growth rate shows a marginally negative association with ROIC, suggesting that rapid expansion may place pressure on capital efficiency.

Overall, the findings indicate that executive education has a limited and context-dependent impact on firm performance in China's real estate industry. CEO education contributes marginally, while CFO education appears more strongly associated with conservative strategies that dampen profitability. By contrast, operational efficiency and financial structure remain the dominant drivers of performance.

6. Conclusions

This study examines the relationship between executive educational background and corporate profitability in China's listed real estate firms from 2018 to 2022. Using multiple econometric approaches to ensure robustness, the findings indicate that executive education has a limited and role-specific impact on firm performance. CEO education shows a modest positive association with asset efficiency (ROA), suggesting some contribution to operational oversight, while CFO education does not exhibit a statistically robust relationship with profitability. Overall, formal academic credentials alone are insufficient predictors of financial performance in capital-intensive, policy-sensitive industries.

From a sustainable development perspective, the results relate to SDG 4 (Quality Education) and SDG 8 (Decent Work and Economic Growth), highlighting that the economic returns to education depend on context and application. Education may enhance managerial capacity, but its contribution to firm performance operates indirectly, primarily through improvements in operational efficiency rather than direct profit maximization. Effective asset utilization emerges as a more critical determinant of profitability than credentials alone.

The findings contribute to literature on executive human capital and corporate performance by showing that returns to education are neither uniform nor universal. CEO education may aid asset utilization and operational oversight, while CFO education appears less impactful, emphasizing the importance of regulatory familiarity, industry experience, and adaptive financial management over formal training. This insight informs SDG 9 (Industry, Innovation, and Infrastructure), suggesting that sustainable performance in infrastructure-related sectors relies on practical decision-making and governance capabilities rather than educational attainment alone.

Theoretically, the study advances upper echelons and human capital theory by identifying boundary conditions in which executive education translates into firm performance: firm strategy, role differentiation, and institutional constraints shape

its effectiveness. The results caution against overemphasizing education as a standalone criterion in executive selection and governance. Instead, integrating formal education with industry experience, operational expertise, and adaptive decision-making is key to enhancing firm outcomes.

By adopting a context-aware and sustainability-oriented perspective, the study provides a nuanced understanding of how executive human capital interacts with firm performance in emerging and highly regulated markets. Education contributes most effectively when applied practically, enhancing operational efficiency, strategic execution, and long-term sustainable growth.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Industrial Air Pollution and Food-Security-Relevant Agricultural Output in Eastern China: Pollutant-Specific Evidence and the Role of Governance

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Abstract: Industrial air pollution poses growing risks to agricultural development, yet evidence remains mixed on pollutant-specific effects and on whether governance capacity can effectively mitigate these damages. Using balanced provincial panel data from 11 eastern Chinese provinces over 2011–2021, this study examines how industrial sulfur dioxide and nitrogen oxides emissions relate to agricultural economic output and whether investment in waste-gas treatment moderates these relationships. We estimate a two-way fixed effects panel model with province and year effects, province-clustered standard errors, and interaction terms between pollutants and governance investment. Results show that nitrogen oxides emissions are consistently associated with lower agricultural output across specifications. In contrast, the estimated relationship for sulfur dioxide is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based robustness checks. We do not find robust contemporaneous evidence that governance investment significantly moderates the pollution–agriculture relationship, suggesting that spending levels alone may be insufficient or that governance effects operate with lags and through enforcement quality. Framed within the Sustainable Development Goals agenda, these findings connect cleaner production and institutional capacity to food security, ecosystem protection, climate-related risk management, and effective public administration. The evidence is also relevant to public health and sustainable communities by highlighting potential co-benefits of prioritizing nitrogen oxides control in industrial regions. By identifying a more policy-relevant priority pollutant and clarifying the limits of investment-only approaches, this study advances SDG-oriented research that links environmental indicators, governance mechanisms, and development performance in a unified empirical design.

Keywords: Industrial Air Pollution; SO₂ emissions; NO_x Emissions; Agricultural Output; Governance Capacity; Waste-gas treatment Investment; Two-way Fixed Effects

Published: Feb 26, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1110>

1. Introduction

Achieving sustainable and resilient food systems increasingly requires understanding how industrialization-driven environmental pressures affect agricultural production. In rapidly industrializing regions, air pollutants generated by industrial activities can impair crop yields, soil quality, and ecosystem services, thereby undermining agricultural development and food security. This concern is closely aligned with the Sustainable Development Goals (SDGs), particularly Zero Hunger, Climate

Action, and Life on Land. At the same time, the effectiveness of pollution control and environmental protection is shaped by governance capacity and institutional implementation, linking this topic to Strong Institutions.

Despite the importance of the pollution–agriculture nexus, existing evidence remains inconclusive in two respects. First, different pollutants may affect agriculture through distinct mechanisms, and empirical results often vary when multiple pollutants are modeled jointly. Second, while governance capacity is frequently emphasized as a key enabler of environmental protection, it is unclear whether governance-related investment can measurably buffer the adverse impacts of industrial emissions on agricultural output in the short run. These uncertainties limit the ability of policymakers to prioritize pollutant-specific interventions and design governance strategies that effectively support sustainable agricultural development.

This study addresses these gaps by examining the impacts of industrial sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emissions on agricultural economic output using a provincial panel dataset covering 11 provinces in Eastern China from 2011 to 2021. The sample includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, and Liaoning. These provinces are economically and industrially intensive, exhibit substantial variation in emissions profiles and environmental governance efforts, and provide a suitable setting to test pollutant-specific effects and governance-related heterogeneity over time.

Methodologically, we employ a two-way fixed effects panel model with province and year effects to account for time-invariant provincial characteristics and common macro shocks. We further introduce an interaction framework to test whether investment in waste-gas treatment (GTD) moderates the relationship between industrial emissions and agricultural output. By distinguishing between SO₂ and NO_x and by evaluating the role of governance investment, this paper makes three contributions. First, it provides pollutant-specific estimates of how industrial emissions relate to agricultural output in an economically critical region. Second, it assesses whether governance investment acts as a buffering mechanism or whether its contemporaneous effect is limited. Third, it discusses how these findings inform SDG-oriented sustainability strategies that balance industrial development, emissions control, and food-system resilience.

2. Literature Review

2.1 Air Pollution, Food Systems, and Governance

Industrial air pollution poses growing risks to agricultural development, yet evidence remains mixed on pollutant-specific effects and on whether governance capacity can effectively mitigate these damages. Using balanced provincial panel data from 11 eastern Chinese provinces over 2011–2021^[1], this study examines how industrial sulfur dioxide and nitrogen oxides emissions relate to agricultural economic output and whether investment in waste-gas treatment moderates these relationships. We estimate a two-way fixed effects panel model with province and year effects, province-clustered standard errors, and interaction terms between pollutants and governance investment. Results show that nitrogen oxides emissions are consistently associated with lower agricultural output across specifications. In contrast, the estimated relationship for sulfur dioxide is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based robustness checks^[2]. We do not find robust contemporaneous evidence that governance investment significantly moderates the pollution–agriculture relationship, suggesting that spending levels alone may be insufficient or that governance effects operate with lags and through enforcement quality. Framed within the Sustainable Development Goals agenda, these findings speak directly to food security and sustainable agriculture, climate action, and the protection of terrestrial ecosystems, while also emphasizing the role of strong institutions in translating environmental investment into measurable outcomes. The evidence is further relevant to public health and sustainable communities by highlighting potential co-benefits of prioritizing nitrogen oxides control in industrial regions. By identifying a more policy-relevant priority pollutant and clarifying the limits of investment-only approaches, this study advances SDG-oriented research that links environmental indicators, governance mechanisms, and development performance in a unified empirical design.

2.2 Industrial Air Pollution and Agricultural Performance

A growing body of research documents that air pollutants can affect agricultural outcomes through multiple channels, including plant physiological stress, reduced photosynthesis, soil acidification, and changes in nutrient cycles^[3]. However, empirical findings vary across contexts due to differences in crop structures, climate conditions, industrial composition,

and measurement approaches. Moreover, studies that model pollutants separately may overstate or misattribute effects when pollutants are correlated or jointly determined by industrial activity and energy use. These considerations motivate a pollutant-specific and joint modeling strategy^[4].

2.3 Governance Capacity and Pollution Mitigation

Environmental governance capacity—captured through regulatory institutions, fiscal resources, monitoring systems, and investment in pollution treatment—can theoretically mitigate pollution damage by reducing emissions intensity, improving compliance, and supporting technology upgrades^[5]. Yet, governance effects may depend on implementation quality, enforcement credibility, and time lags between investment and observable environmental improvement^[6]. As a result, empirical tests of governance buffering effects remain mixed and context-specific.

2.4 Pollutant Heterogeneity

SO₂ and NO_x differ in sources, atmospheric chemistry, and environmental pathways. SO₂ is closely linked to coal combustion and can contribute to acid deposition, while NO_x plays a central role in ozone formation and nitrogen deposition, potentially exerting more persistent stress on crops and ecosystems^[7]. Because these pollutants may co-move with industrial output yet influence agriculture differently, distinguishing their effects is crucial for both interpretation and policy prioritization.

Synthesizing the above, two gaps remain. First, the relative and joint impacts of SO₂ and NO_x on agricultural output are not consistently established in provincial panel settings that control for unobserved heterogeneity and time shocks. Second, it is unclear whether governance-related investment in waste-gas treatment meaningfully moderates the pollution–agriculture relationship contemporaneously. Accordingly, this study tests whether industrial emissions are associated with lower agricultural output and whether higher governance investment weakens these adverse associations, while allowing for pollutant-specific heterogeneity.

3. Data and Methodology

3.1 Data and variables

This study uses a provincial panel dataset for 11 provinces in Eastern China from 2011 to 2021. Agricultural economic output (AEG) is measured by the total agricultural output value. Industrial air pollution is captured by industrial SO₂ emissions and industrial NO_x emissions. Governance capacity is proxied by investment in waste-gas treatment (GTD), reflecting fiscal and administrative efforts to control industrial air pollution. Control variables include the proportion of agricultural fiscal expenditure (LAE), the urbanization rate, and the share of secondary industry in GDP (PSI), which account for agricultural support, demographic and structural change, and industrial structure.

To reduce skewness and interpret coefficients as elasticities, we log-transform AEG, SO₂, NO_x, GTD, and LAE. Urbanization rate and PSI are retained in percentage points. Table 1 summarizes the key variables used in the empirical analysis, including their definitions, measurement units, and data transformations. Agricultural economic output (AEG) and governance investment in waste-gas treatment (GTD) are measured in RMB (or 100 million RMB), while industrial air pollution is captured by SO₂ and NO_x emissions measured in tons (or 10,000 tons). To reduce skewness and allow coefficient interpretation in elasticity terms, AEG, SO₂, NO_x, and GTD are expressed in natural logarithms. The proportion of agricultural fiscal expenditure (LAE) is recorded as a percentage and is log-transformed when it is strictly positive. Urbanization rate and the share of secondary industry in GDP (PSI) are retained in percentage points (level form) to reflect structural and demographic conditions without additional scaling.

Table 1: Variables Description

Variable	Definition	Unit	Transformation
AEG	Total agricultural output value	RMB (or 100 million RMB)	ln(AEG)
SO ₂	Industrial sulfur dioxide emissions	tons (or 10,000 tons)	ln(SO ₂)
NO _x	Industrial nitrogen oxides emissions	tons (or 10,000 tons)	ln(NO _x)
GTD	Investment in waste-gas treatment	RMB (or 100 million RMB)	ln(GTD)
LAE	Proportion of agricultural fiscal expenditure	%	ln(LAE) (if in level >0)

Variable	Definition	Unit	Transformation
Urbanization	Urbanization rate	%	level
PSI	Share of secondary industry in GDP	%	level

Table 2 presents descriptive statistics for the main variables based on 121 province–year observations. The log-transformed measures of agricultural output (\ln_aeg), industrial SO₂ emissions ($\ln_so2_emissions$), industrial NO_x emissions ($\ln_nox_emissions$), waste-gas treatment investment (\ln_gtd), and agricultural fiscal expenditure share (\ln_lae) show substantial cross-provincial and over-time variation, as reflected in their standard deviations and ranges. Urbanization_rate averages 69.645% (ranging from 45.589% to 89.583%), indicating marked differences in development levels across provinces. The industrial structure indicator (ψ) has a mean of 38.902% with a wide spread (15.967% to 52.783%), suggesting notable heterogeneity in the relative importance of secondary industry. Overall, these summary statistics confirm sufficient variation in both pollution and governance-related variables to support the subsequent panel regression analysis.

Table 2: Descriptive Statistics

Variable	count	mean	std	min	max
\ln_aeg	121	7.682	1.239	5.574	9.347
$\ln_so2_emissions$	121	2.654	1.755	-1.966	5.208
$\ln_nox_emissions$	121	3.735	1.019	1.343	5.194
\ln_gtd	121	5.824	1.176	1.553	8.037
\ln_lae	121	3.013	0.909	1.953	5.335
urbanization_rate	121	69.645	12.1	45.589	89.583
ψ	121	38.902	10.487	15.967	52.783

3.2 Empirical Model

We estimate a two-way fixed-effects specification:

$$\ln AEG_{i,t} = \alpha + \beta_1 \ln(SO_2)_{i,t} + \beta_2 \ln(NO_x)_{i,t} + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t}$$

$AEG_{i,t}$ is the dependent variable and reflects the growth of the agricultural economy in region i in year t . Sulfur dioxide and nitrogen oxides are independent variables. $X_{i,t}$ are control variables, including the proportion of agricultural fiscal expenditure (LAE), the proportion of urban population (PUP), and the proportion of secondary industry (PSI). Clustered standard errors at province level account for within-province serial correlation and heteroskedasticity^[8].

Moderation by governance:

To test whether governance buffers damage, we estimate:

$$\ln AEG_{i,t} = \alpha + \beta_1 \ln(SO_2)_{i,t} + \theta (\ln(SO_2)_{i,t} \times \ln(NO_x)_{i,t}) + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t}$$

The interaction item mainly explores whether more investment in environmental governance will buffer the negative impact of industrial waste gas pollution on the agricultural system^[9]. This approach contributes to ongoing discussions about adaptive food planning and spatial justice, especially in rapidly urbanizing contexts where environmental burdens are unequally distributed.

3.3 Evaluation Metrics and Validation

Firstly, by examining pairwise correlations (Table 3), we determined that there was a reasonable linear relationship between the core variables, and the OLS VIF test showed that all VIFs were below 10. There was no significant multicollinearity between the regression variables, and Hausman's comparison suggested that this study should use bidirectional fixed effects. Accordingly, all regressions include province and year fixed effects, and standard errors are clustered at the province level to address within-province serial correlation and heteroskedasticity.

Table 3: Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) ln_aeg	1.000						
(2) ln_so2_emissions	0.647* (0.000)	1.000					
(3) ln_nox_emissions	0.726* (0.000)	0.907* (0.000)	1.000				
(4) ln_gtd	0.327* (0.000)	0.611* (0.000)	0.487* (0.000)	1.000			
(5) ln_lae	-0.855* (0.000)	-0.639* (0.000)	-0.545* (0.000)	-0.404* (0.000)	1.000		
(6) urbanization_r~e	-0.733* (0.000)	-0.501* (0.000)	-0.433* (0.000)	-0.440* (0.000)	0.830* (0.000)	1.000	
(7) psi	0.644* (0.000)	0.813* (0.000)	0.790* (0.000)	0.486* (0.000)	-0.651* (0.000)	-0.418* (0.000)	1.000

*** p<0.01, ** p<0.05, * p<0.1

In the baseline fixed-effects model with both pollutants entered simultaneously, ln(NO_x) carries a negative and statistically significant coefficient, indicating that higher NO_x emissions are associated with lower agricultural economic output after controlling for covariates and fixed effects. By contrast, the coefficient on ln(SO₂) is small and not robustly negative once NO_x is included. Among controls, the coefficient on ln(agricultural expenditure) is negative and significant, while urbanization and industrial share are small and generally not significant in the baseline^[10].

To test moderation, I add ln(GTD) (exhaust-gas treatment investment) and the interaction ln(SO₂)×ln(GTD). The interaction term is statistically indistinguishable from zero in this sample, and marginal-effect calculations show no material change in the SO₂ effect across observed governance levels. Two robustness checks confirm the main pattern. First, replacing raw emissions with population-standardized intensities (per 10,000 people) leaves the NO_x coefficient negative and significant, while SO₂ remains small and not significant. Second, using income-standardized intensities (per 10,000 GDP per capita) delivers the same conclusion^[11]. Across specifications, the sign and significance of NO_x are stable, whereas SO₂ effects are weak and sensitive to definition. Overall, the evidence highlights NO_x as the primary pollutant driving agricultural economic losses in the panel, with no strong statistical support for a governance-based buffering of SO₂ within the observed range^[12].

4. Empirical Analysis and Results

4.1 Baseline Fixed-Effects Results

Table 4 reports the two-way fixed-effects estimates with province and year dummies and standard errors clustered by province (N = 121). Both pollutants enter the model together, alongside controls for agricultural expenditure, urbanization, and the secondary-industry share^[13]. Coefficients are elasticities because the variables are in logs.

Table 4: FE Baseline Regression

Variable	Coef.	Std.Err.	t	P> t
Constant	6.5147	0.6575	9.9088	0
ln(SO ₂)	0.1214	0.0605	2.0056	0.0449
ln(NO _x)	-0.231	0.082	-2.8167	0.0049
ln(Ag. Expenditure)	-0.3074	0.0564	-5.4467	0
Urbanization rate	0.0091	0.0092	0.9913	0.3215
Secondary industry share	0.0097	0.01	0.9644	0.3348
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

*Note: Parenthetical z-statistics(*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$)

The headline result is the negative and statistically significant effect of NOx on the agricultural economy. The coefficient on $\ln(\text{NOX})$ is -0.231 ($\text{SE} = 0.082$, $p = 0.0049$), implying that, holding other factors constant, a 1% rise in NOx emissions is associated with about a 0.23% reduction in provincial agricultural output. This supports the view that nitrogen oxides impose a persistent drag on agricultural performance within provinces over time.

The results also showed that under the control of nitrogen oxide levels and governance measures, if the concentration of sulfur dioxide increased by 1%, agricultural yield would increase by 0.12%. The sign is unexpected if one views SO_2 in isolation, but it is consistent with a conditional relationship: provinces and years with more combustion-intensive economic activity may simultaneously generate more SO_2 and more agricultural income (e.g., through energy access or agro-processing), while NOx captures the more damaging channel. Put differently, once the shared variation with NOx is partialled out by the joint specification and the fixed effects, the partial association of SO_2 with agriculture can turn positive. This pattern motivates the intensity and lag checks reported later^[14].

Turning to the controls, $\ln(\text{Ag. Expenditure})$ is negative and precisely estimated (-0.307 , $\text{SE} = 0.0564$, $p < 0.001$). A reasonable interpretation is policy targeting or timing: higher agricultural spending tends to flow to provinces and years with weaker agricultural performance, or the benefits materialize with lags not captured in the contemporaneous specification. The urbanization rate (0.0091 , $\text{SE} = 0.0092$, $p = 0.322$) and the secondary-industry share (0.0097 , $\text{SE} = 0.010$, $p = 0.335$) are small and statistically indistinguishable from zero. Within-province movements in these shares are gradual and heavily absorbed by fixed effects and year shocks; their incremental explanatory power beyond pollution and expenditure is therefore limited in this setting.

Model fit is high ($R\text{-squared} = 0.9979$), which is common in fixed-effects panels with comprehensive province and year dummies: most level differences are removed by design, and identification comes from within-province changes over time. Inference relies on province-clustered standard errors, making the reported t and p values robust to serial correlation and heteroskedasticity within provinces.

In sum, the baseline establishes a clear adverse role of NOx for agricultural output and a conditional, positive association of SO_2 once NOx and fixed effects are controlled. This differential pattern is precisely why the subsequent sections examine (i) intensity-scaled specifications and (ii) dynamic responses with lags—to check whether the NOx penalty persists and whether the SO_2 sign is sensitive to alternative definitions and timing.

4.2 Governance Buffering Test

Table 5 introduces the governance channel by adding $\ln(\text{GTD})$ —exhaust-gas treatment investment—and the interaction $\ln(\text{SO}_2) \times \ln(\text{GTD})$ to the fixed-effects baseline. Province and year fixed effects are retained and standard errors are clustered by province ($N = 121$). Coefficients can be read as elasticities^[15].

Table 4: Moderation

Variable	Coef.	Std.Err.	t	P> t
Constant	6.4915	0.6377	10.179	0
$\ln(\text{SO}_2)$	0.1213	0.0552	2.1975	0.028
$\ln(\text{GTD})$	0.0133	0.0157	0.8517	0.3944
$\ln(\text{SO}_2) \times \ln(\text{GTD})$	-0.0012	0.0072	-0.1706	0.8646
$\ln(\text{NOX})$	-0.2339	0.0985	-2.3741	0.0176
$\ln(\text{Ag. Expenditure})$	-0.3161	0.0538	-5.8721	0
Urbanization rate	0.0087	0.0083	1.0523	0.2927
Secondary industry share	0.0122	0.009	1.362	0.1732
Observations	121			
R-squared	0.998			

Two findings are immediate. First, the NO_x effect remains negative and statistically significant. The coefficient on ln(NO_x) is −0.2339 (SE = 0.0985, *p* = 0.0176), implying that a 1% increase in NO_x emissions is associated with roughly a 0.23% decline in agricultural economic output, *ceteris paribus*. This confirms the baseline result and underscores NO_x as the pollutant most consistently linked to losses in agricultural performance within provinces over time.

Second, there is no evidence that governance investment moderates the SO₂ relationship in this sample. The interaction term ln(SO₂) × ln(GTD) is −0.0012 (SE = 0.0072, *p* = 0.8646), extremely small in magnitude and far from statistical significance. Substantively, the marginal effect of SO₂ on agricultural output is given by

$$\frac{\partial \ln AEG}{\partial \ln SO_2} = \beta_{SO_2} + \theta \ln GTD$$

With $\beta_{SO_2} = 0.1213$ and $\theta \approx 0$, the slope is essentially flat over the observed range of governance investment. In other words, higher GTD is not associated with a systematic weakening (or strengthening) of the SO₂–agriculture link in the contemporaneous specification.

Looking at main effects, ln(SO₂) remains positive and significant when entered jointly with NO_x and governance (0.1213, SE = 0.0552, *p* = 0.028). This conditional positive association mirrors the baseline joint-pollutant model: after partialling out NO_x and the fixed effects, SO₂ appears to track provinces and years with stronger economic activity, which may coincide with better agricultural outcomes through energy access, processing capacity, or related inputs.

The coefficient of ln (GTD) itself is very small (0.0133, SE=0.0157, *p*=0.3944), indicating that under fixed effects and control measures in place, investment in exhaust gas treatment has no significant impact on agricultural output. This may be related to the instability of environmental investment and endogenous factors in various problematic provinces, leading to a lag in the effectiveness of waste gas treatment investment, so it is impossible to see benefits in the same year or even in the short term.

Control variables behave similarly to the baseline^[16]. ln(Ag. Expenditure) is negative and precise (−0.3161, SE = 0.0538, *p* < 0.001), consistent with countercyclical budgeting or delayed payoffs. At the same time, the insignificant SO₂–GTD interaction highlights the need to probe timing (lagged governance effects), measurement (composition and quality of treatment investment), and heterogeneity (e.g., industrial–agricultural overlap zones) before drawing firm conclusions about the effectiveness of governance in altering the SO₂ pathway.

4.3 Robustness to Intensity Definitions

Tables 6–7 re-estimate the model after converting emissions into intensity measures and taking ln(1+*x*) to stabilize skewness. Table 6 standardizes by population (per 10,000 people); Table 7 standardizes by income (per 10,000 GDP per capita). Province and year fixed effects and province–clustered standard errors are retained (*N* = 121).

Table 6: Robustness Test with Intensity Pop

Variable	Coef.	Std.Err.	t	P> t
Constant	6.7055	0.5406	12.4028	0
ln(SO ₂ per 10k pop + 1)	0.0897	0.0678	1.3236	0.1856
ln(NO _x per 10k pop + 1)	-0.249	0.0854	-2.9162	0.0035
ln(Ag. Expenditure)	-0.3604	0.0545	-6.6168	0
Urbanization rate	0.0145	0.0091	1.5922	0.1114
Secondary industry share	0.0067	0.0106	0.6323	0.5272
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

Table 7: Robustness Test with Intensity LnC

Variable	Coef.	Std.Err.	t	P> t
Constant	6.2216	0.4053	15.3491	0
ln(SO ₂ per 10k GDPpc + 1)	0.0147	0.0957	0.1535	0.878
ln(NO _x per 10k GDPpc + 1)	-0.2338	0.1003	-2.3301	0.0198
ln(Ag. Expenditure)	-0.4135	0.0508	-8.1441	0
Urbanization rate	0.0206	0.0063	3.2696	0.0011
Secondary industry share	0.0044	0.0083	0.5316	0.595
Observations	121			
R-squared	0.9979			
FE (Prov/Year)	Yes / Yes			
SE (clustered by prov.)	Yes			

The core pattern is unchanged: NO_x remains a statistically significant drag on the agricultural economy across both intensity specifications. In the population-standardized model, the coefficient on ln(NO_x per 10k pop + 1) is -0.249 (SE = 0.0854, p = 0.0035). In the income-standardized model, ln(NO_x per 10k GDPpc + 1) is -0.2338 (SE = 0.1003, p = 0.0198). Under the same control conditions, for every 1% increase in nitrogen oxide concentration, the agricultural yield of a province will decrease by 0.23-0.25%.

In Table 6, ln(SO₂ per 10k pop + 1) is 0.0897 (SE = 0.0678, p = 0.186). In Table 7, ln(SO₂ per 10k GDPpc + 1) shrinks to 0.0147 (SE = 0.0957, p = 0.878). Ln (Ag. Endurance) maintained negative values and accuracy in both robustness checks (-0.3604 in Table 6; -0.4135 in Table 7; both p<0.001), indicating that funds may have flowed to underperforming years or there may be lagged effects that the model cannot capture. When standardized by population, the urbanization rate is positive but not significant (0.0145, p=0.111), while it is positive and significant when standardized by income (0.0206, SE=0.0063, p=0.0011). It is possible that as per capita income increases and services improve, agricultural performance also improves. However, compared to nitrogen oxide emissions, this impact can only be seen as complementary and cannot be considered competitive.

5. Discussion

5.1 Results Interpretation: Ecological Disruption and the Role of Governance

This study highlights meaningful heterogeneity across industrial air pollutants in their empirical association with agricultural output. The consistently negative relationship between NO_x emissions and agricultural output aligns with pathways involving ozone formation and nitrogen deposition that can impose persistent stress on crops and ecosystems. By comparison, the SO₂ association appears more sensitive to model specification and scaling, which may reflect that SO₂ emissions are more tightly correlated with industrial energy structure and concurrent economic activity, making its partial association with agricultural output less stable in joint models.

The moderation analysis suggests that governance investment in waste-gas treatment (GTD) does not generate a robust contemporaneous buffering effect in this setting^[19]. This finding does not imply that governance is irrelevant; rather, it points to the importance of implementation quality, enforcement credibility, and potential time lags between investment and environmental improvement^[18]. Future work may benefit from incorporating lag structures, regulatory enforcement indicators, or monitoring coverage measures to capture governance effectiveness beyond expenditure levels^[20].

5.2 Implications and Policy Recommendations

Based on the exploration of government intervention factors, this study proposes several policy recommendations to improve regional environmental planning and promote sustainable development of the agricultural system.

The results speak directly to SDG-oriented sustainability strategies. For SDG 2 (Zero Hunger), the stable negative association between NO_x emissions and agricultural output suggests that industrial air pollution can pose a nontrivial threat to food-

system stability and agricultural productivity^[21]. For SDG 13 (Climate Action) and SDG 15 (Life on Land), the pollutant-specific findings underscore the need to prioritize emission sources and mechanisms that generate more persistent ecological stress^[22]. For SDG 16 (Strong Institutions), the limited contemporaneous moderation effect of GTD highlights that institutional strength should be evaluated not only by spending levels but also by enforcement, accountability, and effective implementation.

Policymakers should prioritize NO_x reduction strategies in regions where NO_x emissions are persistently associated with lower agricultural output, including targeted controls on high-emitting industrial sources and energy-use adjustments. Governance investment should be paired with implementation mechanisms—such as monitoring capacity, inspection frequency, compliance incentives, and enforcement credibility—to ensure that spending translates into measurable environmental improvements^[23]. Interventions should be regionally differentiated: provinces with heavier industrial structures and higher emission intensity may require stricter standards and more rigorous enforcement, while provinces with more agriculture-dependent economies may benefit from integrated land–air management strategies that protect agricultural resilience^[24].

6. Conclusion

Using provincial panel data from 11 eastern Chinese provinces over 2011–2021, this study examines pollutant-specific effects of industrial air pollution on agricultural output and assesses whether governance investment in waste-gas treatment moderates these effects. The evidence indicates that NO_x emissions are consistently associated with lower agricultural output, while the SO₂ association is less robust and becomes statistically indistinguishable under alternative specifications and intensity-based checks. We do not find robust contemporaneous moderation effects of GTD, suggesting that governance spending alone may not immediately buffer pollution damages without effective enforcement and implementation quality.

These findings provide SDG-relevant insights for sustainable development: they highlight pollution-related risks to agricultural production, support prioritization of effective emissions management strategies, and emphasize the role of strong institutions and accountable implementation in translating governance inputs into outcomes. Future research could incorporate lag structures and enforcement-based governance indicators to better capture dynamic policy effects.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Crossing Generations in the Digital Age: Silver-Haired Influencers, Digital Inclusion, and Social Sustainability on Douyin

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Abstract: This article examines how silver-haired influencers on Douyin foster intergenerational communication and digital inclusion in China's rapidly platformized society. Through analysis of popular short videos and interactive comment spaces, the study shows how everyday practices such as cooking demonstrations, personal storytelling, health knowledge sharing, and rural life performances become shared symbolic resources through which older and younger users negotiate meaning and social belonging. Drawing on social constructivism and symbolic interactionism, the findings reveal how older adults develop agency through platform-mediated interaction and the co-creation of intergenerational scripts in comments, duets, and mimicry. The study further identifies the ambivalent role of algorithmic governance, which amplifies positive and emotionally connective narratives while simultaneously constraining representations of aging. By linking digital participation to intergenerational well-being and social inclusion, this research contributes to SDG 3 (Good Health and Well-being), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Communities), highlighting the importance of inclusive platform governance for social sustainability.

Keywords: Intergenerational Communication; Digital Aging; Silver-Haired Influencers; Platform Agency; Social Inclusion

Published: Feb 26, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1111>

1. Introduction

1.1 Research Background and Importance

Intergenerational communication and digital participation are increasingly recognized as central concerns within the United Nations Sustainable Development Goals (SDGs), particularly those related to social inclusion, well-being, and sustainable communities. As population aging and digital transformation unfold simultaneously, ensuring that older adults can meaningfully participate in digital environments has become closely linked to SDG 3 (Good Health and Well-being), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities and Communities)^{[1][2]}. From this perspective, the digital engagement of older adults is not only a matter of technological access but also a key indicator of inclusive and sustainable social

development. Examining how older adults communicate, gain visibility, and build social ties on digital platforms therefore offers an important lens for understanding the social sustainability of platformized societies.

With the rapid aging of the population and the continuous advancement of digital transformation, the extent to which the elderly participate in the digital environment has become an important indicator for measuring social inclusion and sustainable development. In China, policies promoting active aging and digital inclusion further encourage the elderly to use platforms such as Douyin for socializing, self-expression and intergenerational communication. It is precisely in this environment that silver-haired influencers have rapidly gained popularity among the public. They challenge stereotypical constructs linked to age and take up important positions in intergenerational communication and social innovation. Despite the rising scholarly interest, existing scholarship remains largely focused on influence, popularity, or mediated representations, therefore offering little insight into the micro-interactional practices by which older content creators develop intergenerational understanding^{[3][4]}. Indeed, studies very often overlook how content creators and younger users make meaning together in comment threads and co-creative videos. Moreover, how technical architectures-from algorithmic recommendations to more interactive affordances-shape older adults' communicative presence is often paid insufficient attention to, again, in the literature^{[5][6][7]}. And finally, how exactly silver-haired influencers contribute to social inclusion and sustainable development remains underexamined, as much of the literature so far is descriptive rather than analytically oriented^{[8][9][10]}.

This research adds new insights to aging and media studies. It adopts a process-oriented, micro-analytic focus that examines how older adults negotiate identity and agency within Douyin. Rather than emphasizing follower counts or the mere presence of older creators, this study centers comment-based dialogue, collaborative videos and other spaces where intergenerational meaning is negotiated. It also highlights the structural conditions that affect the participation of the elderly, demonstrating how their visibility, knowledge sharing and cultural practices have emerged through rapid technological changes and the opportunities and limitations created by advice, interactive tools and computer-mediated communication. Moreover, this work advances debates on social inclusion and sustainability by examining how silver-haired influencers communicate around health, traditions, emotional bonds, and environmentally responsible practices, positioning older adults as active contributors to social cohesion.

1.2 Research Objectives

This project will focus on analyzing the top 44 silver-haired influencers as well as their most representative videos on Douyin, with a total of 132 pieces, through qualitative content analysis. Moreover, this project explores how the functions of internet platforms, such as algorithms, affect intergenerational communication. Conceptually, this project will treat intergenerational communication as a form of “role-taking” as defined in symbolic interactionist theories, with the internet-enabled short videos being the platforms for this form of intergenerational interaction.

Table1. The Objectives and Questions of Study

Research Objectives	Research Questions
RO1:To explore how silver-haired influencers establish inter-generational communication with youth	RQ1: What content creation and interaction strategies do silver-haired influencers use to foster dialogue?
RO2:To reveal how digital platforms empower silver-haired influencers to facilitate understanding	RQ2: How do platforms like Douyin enable and shape the intergenerational connections created by these influencers?
RO3:To map the pathways by which silver-haired influencers promote social inclusion and sustainability	RQ3: How do the communicative practices of silver-haired influencers advance social inclusion and sustainability?

2. Literature Review

Digital inclusion and intergenerational equity are increasingly emphasized within the United Nations Sustainable Development Goals as foundational elements of social sustainability. The SDG framework highlights that meaningful participation in digital life is closely connected to well-being, equality, and the resilience of communities, particularly in aging societies^{[1][2]}. From this perspective, digital platforms are not merely technical infrastructures but social spaces

where inclusion is enacted through everyday interaction, communication, and knowledge exchange across generations. Intergenerational equity within the SDG agenda therefore calls for attention to how older and younger users engage with one another, negotiate visibility, and co-construct social meaning in digital environments. This interdisciplinary framing links policy-oriented sustainability goals with micro-level analyses of communication, interaction, and platform governance. It provides the conceptual foundation for the following review, which examines intergenerational micro-interactions, platform architectures, and pathways toward social inclusion and sustainable development in platformized media contexts.

2.1 Micro-Interactions between Older Content Creators and Younger Users

The rising presence of older adults as digital authors has offered new opportunities to share knowledge, personal narratives and emotional presence, ultimately fostering emerging forms of intergenerational connectedness^{[4][11]}. However, many current studies concentrate on how a video contributes to social impact at the general level or re-imagining of an aging identity and not enough to micro-level mechanisms that organize interactive meaning construction in short videos and comment threads^[3]. Recent research suggests that intersubjectivity involves negotiated meaning, relational language practices and symbolic resources for the way identity and emotions are circulated digitally^{[12][13]}. Older adults and younger participants connect around a shared experience, humor, affect^{[14][15]}, but the processual and relational dynamics of these kind of communications are under-researched^{[16][17][18]}. Symbolic interactionism also can be quite useful for analyzing the coconstruction of meaning and self-identity in these interactions^[19]. But, further empirical research is needed to help elucidate the specific processes by which seniors and young follows develop and maintain cross-generational relationships in virtual space^{[20][21]}. This study contributes to this gap by discussing the embedded, micro-interactional processes that occur via video performance and comment-based discussion.

2.2 Digital Platforms and the Architecture of Intergenerational Communication

As digital media increasingly influences cultural production and intergenerational interaction, organising the flow of information with recommendation algorithms, community structures and play rules^[5]. These spaces are sociotechnical systems which impact the visibility, self-presentation, and relational involvement of older adults^[22]. Recommendation policies could extend opportunities for silver-haired influencers' and reduce thresholds for younger participants to come into contact with their work, while features such as hashtags, comment sections, gifting options all contribute to new communicative space^{[6][7][23]}. Yet, studies to date have continued to focus on the technical opportunities of platforms and tend to say little about how these architectures structure everyday modes of relationship-making between silver-haired influencers and their younger audiences^{[24][25][26]}. From a social constructivist point of view, platforms act as cultural contexts for the production of meaning and negotiation of social identity^[27]. Platform empowerment is based on affordances, community norms and wider social norms^[28]. However, little is known about the role that these infrastructures play in facilitating older people's intergenerational communication practices and how such connections sustain over time. Addressing this gap, in this study we examine how Douyin's governance configurations and affordances mediate both the form and limits of intergenerational communication.

2.3 Pathways toward Social Inclusion and Sustainable Development

This paper sets forth the investigation of the contributions of older adults' digital participation in achieving social inclusion and sustainability in the digital society of China. By storytelling, involvement, and participatory practices, silver-hair influencers embody public-facing contributors, contributing to health promotion, bond, cultural heritage, and public advocacy^[29]. Empirical studies show that their involvement is associated with reduced prejudices, improved cohesion, and increased collaborative efforts between different ages, although comprehensive theoretical analyses of the same remain uncharted^[30]. Social inclusion, as achieved through equal involvement, free expression, and joint endeavors across different ages, is further supported through older producers' active contributions, such as echoed knowledge distribution^{[8][31]}. Although silver-haired influencers play their roles in establishing cultural memory and supporting sustainability, which encompasses health practices, fraud protection, expertise in crafts, and other environmental issues, the exact pathways through which these endeavors contribute towards better social inclusions remain uncharted^{[10][32][33]}. Some studies have also highlighted how young users learn through Douyin depending on emotional and cultural needs, which further shapes the way intergenerational

meaning is formed^[34]. Social constructivism mirrors the interactional pathways of meaning, identity, and negotiation, whereas symbolic interactionist theories deal with the principles of role taking, role undertaking, and role recognition, although none remain systematized as empirical studies till now. By this background, this empirical study fills the existing gaps in this fascinating topic through its initiating pathways, studying the contributions of older producers' communicational practices, focusing on pathways towards social inclusions, as well as sustainability within the digital environment of China.

3. The Chinese Context

China is facing a challenge in the rapid process of population aging^{[9][35]}, yet with changing images of older adults by media presentation and calls for active aging from national policies^{[29][36]}. The fast digital transition further stimulates the connection of older adults to digital spaces, with them now using digital technology today not only as content consumers but increasingly also as content producers in new media environments^{[30][37][38]}. New forms of participation start to appear with more and more elderly people using digital tools^[39] allowing them to communicate and present themselves in public life. Social media platforms such as Douyin have played a key role in this process, since they shaped how people view the elderly and how they interact with younger users^{[32][33][36][40]}. These changes remind people about the significance of understanding how social and technological changes taking place in the digital space have shaped how people age, how families connect, and how social inclusion operates today^{[35][41][42][43]}.

During these turns, silver-haired influencers on Douyin have emerged by creating short videos, livestreams and interactive content around health, companionship, fraud prevention, family memory, handicrafting and rural renewal^{[9][44][45] [40]}. Their personal modes of storytelling interest young viewers, engaging them in active commenting, collaborative videos and challenges^{[8][46][47]}. Douyin's algorithm recommendations and community dynamics push the content to a variety of user audiences^{[32][33][40]}, enabling intergenerational communication, shared identity, and emotional connection^{[36][44][48][49]}. The open and participatory nature of the platform nurtures identity formation, new forms of community and so on^{[31][50][51][52][53]}. However, so far, the research on Douyin influencers has mainly concerned these popularity trends or mediated images^{[10][35]}, thus the interactional strategies that silver-haired influencers use to do this How does Douyin decrease barriers for participation of older adults and how do these practices maintain solidarity between generations and create new culture have not yet been studied^{[40][43][54]}. A systematic study of these communicative mechanisms is important to unlocking China's digital transformation in an aging society^{[36][52][55]}, and provides new perspectives on cultivating intergenerational understanding and social inclusion^{[18][40][44][53][56]}.

4. Research Methods

4.1 Methodological Approach

The research is framed by an interpretive qualitative approach based on social constructivist and symbolic interactionist grounds. These views understand communication as a process of involving an ongoing negotiation about meaning, identity and social relations. I use qualitative content analysis to understand how silver-haired influencers and younger users co-construct meanings through short-video performances and comment interaction. Instead of looking at normative figures, the analysis shows how digital agency and intergenerational communication are practised by older people through symbol work, role-taking, everyday narratives and interactional practices. Informed by these theoretical commitments, the analysis considers how communicative acts in form of videos, captions and comments mediate meaning making, identity practices and collaborative sense-making. This perspective then allows for a close analysis of how older producers, on the one hand, and younger audiences, on the other, are binding relational ties and co-producing generational scripts in the sociotechnical environment of Douyin.

4.2 Sampling and Data Collection

Sampling was opportunistic and purposive, we identified 44 active and popular silver-haired influencers on Douyin. Age identification was based on silver-haired influencers' self-descriptions, platform labels, or media reports. Selection criteria included: (1) a follower base of at least a moderate scale, (2) consistent content production over the previous six to twelve months, (3) a primary focus on everyday life themes such as family interactions, cooking, traditional skills, health,

companionship, rural life, or fraud prevention, and (4) exclusion of institutional, commercial-only, or inactive accounts. For each influencer, the three most-liked and most-viewed videos during the data collection period were retrieved, resulting in 132 video entries supplemented by their associated public comments and visible engagement metrics. These videos represent the silver-haired influencers' most publicly salient content and the interactional spaces where intergenerational communication is most active. Each video was evaluated according to a standardized set of eight analytic dimensions, which structured the process of annotation and interpretation (see Figure 1). There is also limitations like potential sampling bias since focusing on top-performing videos foregrounds the most visible and engaging moments of intergenerational interaction, which suits the research objectives but may underrepresent routine, less successful, or conflictual exchanges. All data were collected manually and archived for analysis, permitting deep immersion in the material while safeguarding analytic accuracy and interpretive depth; reflexive dialogue among team members served as a check on premature closure, and supported a cooperative search for emergent patterns and alternate readings.

Figure 1. Analytical Dimensions for Silver-haired Influencer Short Video Evaluation

Understanding video analysis: From broad themes to granular details.



4.3 Analytical Approach and Theoretical Framing

The analytic process was informed by the interpretative and assumption of social constructivist and symbolic interactionist. Videos and their comment threads were thus taken to be sites of negotiated meaning and role-taking in which older fans and younger viewers co-constructed the norms, identities, and gesture systems in play within intergenerational encounters. This theoretical frame oriented the analysis to consider how performances were co-constructed in loops of feedback, how audience responses reframed silver-haired influencers' self-presentation, and how features afforded or constrained these dynamics. For systematic interpretation, the research team adopted eight analytic dimensions that provided a uniform perspective between short-video content and interaction fields (Table 2).

Table 2. Analytic Dimensions Used in Coding

Dimension	Focus of Analysis
1. Topic/Theme	Core subject of the video
2. Emotional Expression	Affective tone conveyed by creators and audiences
3. Storytelling Structure	Narrative strategies and sequencing
4. Language/Rhetorical Style	Verbal choices, humor, framing devices
5. Invitations to Interaction	Prompts encouraging participation or dialogue
6. Platform Features	Visible uses of duets, hashtags, filters, stitching
7. Generational Address	Explicit/implicit references to age groups
8. Knowledge Transfer	Demonstration of skills, advice, life experience

Open coding was applied to the entire dataset in an iterative manner. The accompanying comment thread for each video was independently coded, capturing both explicit text as well as shifts in tenor or affect and moments of generationally confirming, reversing, or renegotiating roles. Codes that were often coded in close proximity with one another were collapsed into subthemes (eg, repetitive points on “family recipes,” “health routines,” and “life advice” constituted similarly themed subthemes around intergenerational exchange of knowledge, while jokes or shared memories formed themes like collaborative study or public intimacy). Interim concepts that pertain to one another were subsumed or collapsed into overarching themes through recursive interpretation. Coders repeatedly revisited particular videos in order to further clarify category boundaries and to test alternative interpretations, exploring how meanings were negotiated between performance and audience response. The method focused on cross-reading across videos and comment sections, enabling the research team to follow how the narrative and expressive tactics of silver-haired influencers were echoed, reframed or challenged by younger audience members.

Confidence was also achieved through a negotiated-agreement methodology. Team members coded their posted samples separately and convened to resolve any differences in coding. Regular coder meetings, shared coding sheets and reflexive memos promoted interpretive coherency across the different stages of the process, enabling deep immersion in the data to preserve authenticity and trustworthiness of interpretations, while ongoing team-stage reflexivity helped prevent premature closure and encouraged a collective search for emergent patterns and alternative readings.

4.4 Ethical Considerations

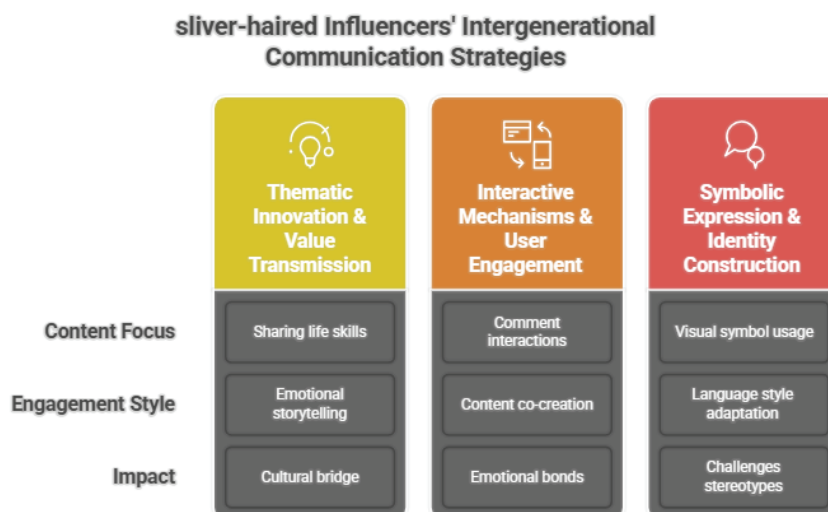
All of the data sources for this analysis are publicly available Douyin content. In order to minimize identifiability risks, as the participants included older people who are often perceived as a vulnerable population, usernames were substituted with pseudonyms, and we did not supply specific personal information or addresses that were not already publicly available in mass media. Great pains were taken not to disseminate anything that was controversial or which could be easily misconstrued. No private communications or non-public data were accessed, and all work was done in accordance with ethical standards on research involving digital trace data.

5. Findings

5.1 Intergenerational Co-Creation and the Transformation of Older Adult Identity

Responding to RQ1, in this section we demonstrate how silver-haired influencers position themselves by developing strategies of content creation and interaction that foster intergeneration dialogue (Figure 2). Across the data set, silver-haired influencers developed participatory meaning-making spaces that cut across routine practices, emotional exchange, and creative re-readings of age.

Figure2: Silver-haired netizens' diverse creations deepen intergenerational communication season



Influencers believed that such routine activities like cooking, crafting, or storytelling were invitations for younger audiences. Rather, the videos played a greater role as stimuli for youth audiences to imitate, modify, or supplement their own narratives. In the series of “Grandma Pan’s” culinary videos, audiences shared their own experiences in recreating Grandma Pan’s dishes, while “Old Qiao’s” crafting videos invited audiences to supplement their own experiences with such family histories. Such interaction began with the informal development of co-creation. This was further facilitated through the comments found within such videos. Young audiences began associating such information with their family experiences (“This is something that I learned for Grandma’s own use”), or with their own visions of their ideal older self (“This is something that I can hope for in terms of aging”). Such dialogue contributed to the development of emotional intensity focused on shared intimacy that reached beyond the confines of the video. Influencers began developing their own identity expressions, working beyond simple stereotypes that were associated with aging. Humor, fashion, as well as sophisticated identity presentation, as seen in “Grandma Wang’s” catwalk performances that presented “later” life as dynamic, engaged, as well as even desirable, began with comments that growing older was something that they “looked forward” to.

From the symbolic interactionist point of view, such cross-generational communications can be seen as demonstrating meaning-making and identity-construction as a product of perpetual role-taking^{[19][3]}. Silver-haired influencers do not only deliver knowledge, engaging in more interactional hinting that enables young audiences to envision their own future roles reflected in phrases like ‘the older self that I would like to be,’ but also position the YouTuber as their conversational partner, as opposed to ‘experts.’ By their imitation, joking, storytelling, and supplementing, youth’s mimetic, joking, or storytelling practices are a form of interactional, mutualistic role-taking, informing others about their own impression of the silver-haired influencers’ identity, as well as youth’s expectations from ‘the elder.’ Such dialogue-like practices form a shared, mutually believed ‘meaning’ in being ‘a good elder,’ ‘a modern elder,’ and ‘a ‘relatable’ elder.’

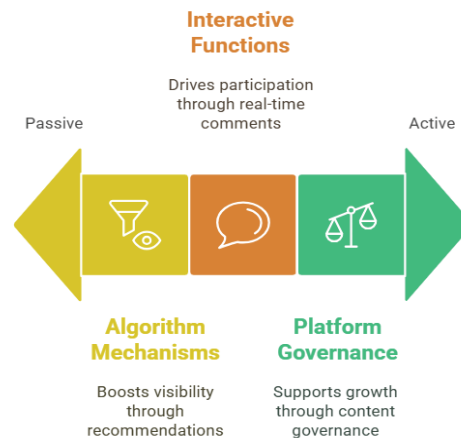
Social constructivism itself explains that these meanings are not just individualistic but co-constructed in platform-enabled settings. The comment threads and co-created videos are micro-level spaces where both generations mould age, authority, intimacy and belonging each in partly overlapping ways. Older and younger audiences transpose social roles through acts of performance through teaching, joking, remembering together and aging via participatory participation. The result is a negotiated, dynamic repertoire of generational symbols that extends far beyond the family and into shared resources in the cultural worlds of Douyin.

5.2 The Structural Role of Douyin in Empowering Intergenerational Communication

This is how the Douyin code’s algorithmic design, interaction affordances, and value system condition the space of possibilities and limits for intergenerational communication are explored in response to RQ2 (Figure 3). This influence was enacted through the circulation of content, the organization of participation, and the amplification of particular normative scripts.

Figure3: The structural role of Douyin in empowering silver-haired influencers to communicate across generations

Douyin's support for silver-haired influencers ranges from passive to active



Among the sample, videos tied to concepts like family, tradition and earthy wisdom seem to have broad appeal. Douyin's tagging and recommendation logic (e.g., the "elder daily life" category and "grandparents' beautiful lives", which enabled circulation across generations) that also contributed to broadening the audience for silver-haired influencers^{[32][40]}. Interaction features, such as comments, duets, stitching and challenges promoted reciprocal engagement. Several silver-haired influencers answered viewer questions, reacted to stories people shared or incorporated fans' ideas into follow-up videos. These were the features, which facilitated a feedback loop where meaning was hashed out across interaction rather than cemented in the original posting. The governance values of Douyin also had a molding effect. Meanwhile, content in line with the platform's preferred narratives of "positive energy," harmony and family togetherness tended to be more stably promoted. However, posts on loneliness, conflict or frustration were not circulated that much in the algorithmic feeds which indicate that visibility is linked to certain normative desiderata.

Under a social constructivist perspective, recommendation systems and value-tagging are used to subtly shape what type of interactions are most legible, acceptable or promotable by the platform^{[5][27]}. The algorithmic and interactional structures of Douyin serve as active mediators in the coproduction of symbolic frontiers for generational communication. Instead of being a neutral channel, however, the platform reinforces narratives that resonate with such broader cultural values as warmth for family, continuation and "positive energy." This curation implicitly defines what constitutes legitimate generational interaction, incentivizing silver-haired influencers toward scripts that emphasize concord and care and the transmission of culture. Therefore, platform governance is closely connected to meaning production, as it dictates which identities are made visible and what relational practices become aesthetically appealing to users that influence their expectations before they even interact with a profile.

Symbolic interactionist theories may shed some light on this process. Elderly individuals must decode the symbolic language presented through platforms such as Douyin, reading signs such as 'tags,' 'trending sounds,' and so on, so that their own performances will adapt accordingly. Young individuals, in turn, would also be reading the symbolic interactions presented through the creations of other users within this predesigned symbolic space, reinforcing some notions of aging, although implicitly minimizing others. Thus, as users interact with platforms, this symbolic interaction loop is further reinforced, increasing specific 'performances' based on 'algorithms,' which provide other users with 'responses,' further compounding Douyin's own symbolic evaluative frameworks. Thus, Douyin's own symbolic interactionist landscape further cements the space not only as a ground for inter-generational interaction but also subtly shapes its governance dynamics through notions of forms of aging.

5.3 The Social Role of Silver-Haired Influencers

This subsection responds to RQ3 in explaining how silver-haired influencers enhance social inclusion and sustainability

through health communication, value reshaping, and green behaviors (Figure 4). Their efforts democratize participation across generations by rendering ordinary sense, moral imagination and environmental responsibility as publicly shareable.

Figure 4 . The Social Role of Silver-haired Influencers



Structured demonstrations of nutrition practices, levels of physical activity, bedtime routines or fraud prevention prompted individuals to mimic these behaviours in their lives; frequently they left comments indicating as much (“I’m was taught this routine from Grandpa”). This trend mirrors the strength of inter-generational communication^{[8][15]}. Meanwhile silver-haired influencers subverted normative images of ageing. The use of humor, style and storytelling with an emotional connection helped replace the deficit frames, which led younger viewers to admire what they were seeing or reattach to memories of their own family. Such exchanges had promoted recognition across age groups while viewed ageing as socially meaningful rather than marginalized^[48]. Influencers also invited their audience to reflect on the themes of sustainability and rural revival. Portraying low-waste, resource-reuse or eco-friendly farming practices in “daily life” settings offered opportunities to put similar routines to the test and swap stories about their outcomes, according to accounts such as “Grandpa Zhao in the Village” would inspire young individuals. These stories were part of what made sustainability a habit for generations.

Symbolic interactionism helps light up the process of how silver-haired influencers archive ordinary acts such as cooking, storytelling and health-bragging into symbolic commodity for collective identity doing. These are performances, stages that older people use in order to demonstrate their competence, emotionality and social relevance and then invite younger audiences to listen by opening themselves up to receive memories, anxieties or hopes. In multiple acts of gifting, regenerating symbols of care, wisdom and new life are passed from generation to generation in a widespread circle of beneficence and if recognition is being enhanced it can be assumed that community is as well. Such a process of meaning creation helps to break the stereotypes of fragility or detachment from society, revealing that aging is a dynamic place that constantly participates in society.

In this social constructivist approach, such practices also demonstrate digital culture’s productive use in facilitating inclusive dialogue. By older persons defining issues of well-being, fraud, or ecologies as issues that concern multiple ages, they use such issues to define a space of mutual concern that draws youth in^{[32][51]}. Such practices of social interaction mutually define a discourse of social membership that imagines older persons as producers within the public well-being, not as merely being its beneficiaries. But such conduct within a social constructivist perspective equally emphasizes the fragility of this symbolic enhancement, as, for example, the harmony that digital platforms promote as inclusive can mask difficult aspects of aging as well, as digital inclusion remains dependent upon algorithms’ conditional visibility.

Despite the dominant tendencies that suggest a form of intergenerational co-construction, dialogue, and expanding social participation, the results also demonstrate some points of tension that complicate this positive dynamic. Throughout the collected dataset, occasional points of misunderstanding were found, such as instances where young users satirically critiqued traditional practices, questioned the applicability of older users’ advice, or reacted with annoyance towards moralistic

undertones. Also identified were conversations that were broken up, with the young users dropping off or abruptly changing topic, as if sapped of shared group interests. Several silver-haired influencers were found to be criticized for their ‘excessive positivity,’ forced acting, or monetary collaborations, where some viewers were skeptical of their authenticity or toning. Finally, the dynamics of the platforms presented additional limitations, whereby some videos, especially those discussing sickness, loneliness, or systemic gripes, were found to be less ‘algorithmically supported’ with noticeably quieter spaces of interaction, suggesting that not all elements of aging were easily or neatly slotted within desirable scripting formulas. Such negative instances did not refute the positive tendencies found within this corpus, but merely further asserted that intergenerational dialogue within Douyin was neither seamless nor inclusive. Rather, the pathways of intergenerational dialogue, recognition, and construction, as identified within this text, would be better located as uneven.

6. Discussion

6.1 Intergenerational Communication as Symbolic Negotiation: Strategies and Social Dynamics

The story of intergenerational communication on Douyin is best understood as a process of ongoing symbolic negotiation, in which silver-haired influencers and youth audiences continually co-produce meaning, identity, and recognition^{[4][19]}. Drawing on symbolic interactionism, this study found that silver-haired influencers rarely present themselves as fixed authorities; instead, they invite dialogue, adaptation, and sometimes gentle challenge from younger viewers, a dynamic noted in recent studies of micro-interactions in digital spaces^{[3][12]}. Their content strategies often blend the sharing of personal memories, demonstrations of practical skills, and displays of family ritual, echoing Goffman’s account of the social stage, where performance is always shaped by audience feedback and collective improvisation^{[11][13]}.

What different in Chinese is that people combine family stories with public self-presentation. This is becoming increasingly common as the elderly learn to play new roles in digital life^{[9][29]}. Many videos have contents about elderly people cooking traditional food or talking about daily life, which are more like scripts that others can join in rather than just individual performances. The behavior of viewers’ adding comments, creating duets or copying videos creates new shared meanings^[40]^[48]. with increasingly engagement of people, these scripts are constantly changing and enriching. The digital space in the West usually looks different that they tend to divide age groups or push older creators aside^{[5][8]}. On Douyin, people copy videos to each other and communicate across generations in a fast and direct ways. These behaviors indicate that users value social intimacy and shared meanin^[57].

But these interactions are not always smooth. People use titles such as “wise grandparents” or “fashionable elders” which changed over time. They acquired new tones like humor, hope or even resistance^{[35][42]}. These changes indicate what people’s needs and concerns are when considering age and authority. This process is positive and continuous that it reflects both the long-term cultural concepts and the limitations of platform settings^{[55][56]}. True intergenerational conversations do not remain unchanged, instead, people constantly redraw boundaries, identities and expectations^{[16][17][58]}.

6.2 Platform Power and Structural Ambivalence: Algorithmic Inclusion and New Hierarchies

Digital platforms like Douyin aims on opening up space for free expression, but they also play the key role of powerful mediators by determining who is included and who is excluded. This influence is obvious to silver-haired influencers^{[5][22]}. Social constructivist theory claims that the digital space is never neutral, each platform has its own values and goals reflected in the way content moves and gains attention^{[26][27]}. In China, Douyin platform uses its recommendation system and tools to promote “positive energy” stories and intergenerational relationships. These characteristics help the elderly gain early recognition and establish connections with the young^{[6][23]}.

The data shows a clear tension. This algorithm can push silver-haired influencers to the mainstream, help them quickly build or join in communities while guide them towards familiar themes. The content about family, nostalgia, health and rural life reflects the platform’s own choices and values^{[7][40][59]}. This model differs from many Western platforms, where viral content typically stems from conflicts, novelty or trends that focus on young people^{[5][8]}. In China, Douyin’s gentle guidance style has led to a consensus on people’s content preferences, but it has also narrowed down the types of sounds that can stand out^{[24][25]}. Moreover, Douyin’s interactive tools have shaped the way users engage with the platform: comment threads, video collaboration and challenges have created an active and lively form of participation. These characteristics also reinforce

certain social patterns and expected behavioral patterns^{[7][44][49]}. Young audiences may shower silver-haired influencers with praise and imitation, but these gestures sometimes reinforce established hierarchies or mask subtler forms of regulation and marginalization^{[31][56]}. The logic of commercial partnership, training, and governmental certificization further incorporates ‘silver-haired’ influencers into the economy of the platform, as well as positions their use as symbolic markers of unity and progress^{[32][55]}. Indeed, structural empowerment within both Chinese culture and within the ‘Western’ experiences is inherently oxymoronic: enabling forms of agency, yet producing new forms of stratification and erasures^{[26][27]}.

6.3 Symbolic Circulation and the Ethics of Social Sustainability: Toward Deeper Inclusion

The impact of the silver-haired influencer can be seen more in their public role as advocates for health, information, and sustainability^{[29][48]}. But the meaning of their digital existence is not simply found within the practical movement that impels those practices^{[15][32]}. But at the same time, there is an other side of a coin in Chinese that the transformation of private wisdom. Platform and community also actively promote the amalgamation of family stories, artisanal knowledge, local customs/lifestyles into a co-created public resource^{[40][44][51]}. These creative activities broaden the dimensions of social inclusion, enabling younger generations to join the co-formation of collective memory and future possibility^{[33][48]}.

However, while social sustainability is sought on digital platforms, there is a danger of it being superficial and based on only what looks good and feels right^{[10][36]}. This focus on “positive energy” and harmonious stories helps build warm relationships among generations, and can also limit open differences and hide many real aging struggles^{[35][52]}. In the Western environment, the lack of strong algorithmic control may allow more voices to emerge while it may also lead to more division and exclusion^{[5][8]}. Against this backdrop, establishing a digital space where all sounds can be heard has become an important goal. This goal is particularly meaningful for those who do not conform to the main interests of the platform^{[31][33]}.

Social inclusion requires people’s constantly attention to how visibility and silence function in online public spaces^{[8][32]}. The videos of silver-haired influencers offered opportunity for intergenerational communication which may influence young users’ views on age while reveal the limitations of protocols on the platform^[56]. The digital ethics of care and sustainable development not only come from the stories shared by everyone^[47], but also from the stable work of listening to marginal voices^[40].

From a Sustainable Development Goals perspective^{[1][2]}, the findings of this study contribute to ongoing debates on how digital participation can support social sustainability in aging societies. By demonstrating how silver-haired influencers engage in intergenerational meaning-making, everyday care practices, and knowledge sharing, the study provides empirical support for SDG 3 (Good Health and Well-being) by highlighting the psychosocial benefits of recognition, dialogue, and emotional connection in digital spaces. At the same time, the negotiated and relational forms of participation observed on Douyin speak directly to SDG 10 (Reduced Inequalities), as they challenge age-based marginalization and expand opportunities for older adults to remain visible and socially relevant. Finally, by situating these interactions within platformed communities shaped by algorithmic governance, the analysis advances SDG 11 (Sustainable Cities and Communities) by showing how digital environments can function as spaces of social cohesion, while also revealing the ethical tensions and structural limits that must be addressed to ensure long-term social sustainability.

Conclusion

This project explores the reality of life in China’s developing online world by tracking the experiences of silver-haired influencers on Douyin platform. The results show that this digital space is active and shifting. Elderly people are not passive users here, instead, they take actions to reshape social expectations along with open up space for the realization and recognition of dialogue. Intergenerational relationships seem to be a continuous work rather than a fixed pattern. Silver-haired influencers invite young people to join small rituals of memory making which are creative and concerned to offer flexible forms of communication. These silver-haired influencers are not legendary figures but ordinary people who were allowed to speak up on digital platforms like Douyin. Their existence grows through the rhythm of algorithms, the preferences of the audience and the continuous search of connections among users by mobile phones. From this perspective, China’s digital aging is not merely about narrowing the generation gap, but also a creative process in which people imagine new ways to view each other, learn from one another and remain present in the social imagination of different ages. Meanwhile, this study

demonstrates the hybrid nature of digital licensing. Platforms can enhance the voices of the elderly, but they also shape what can be seen and heard. Some stories gain strength, while others may be overlapped. The work of building tolerance will never end. silver-haired influencers demonstrate agency capabilities in a space that offers permission but imposes restrictions. Their work always involves negotiations and sometimes mild resistance.

In relation to the Sustainable Development Goals^{[1][2]}, this study underscores the importance of digital inclusion and intergenerational communication as key dimensions of social sustainability. The experiences of silver-haired influencers on Douyin illustrate how older adults can actively contribute to well-being, social cohesion, and inclusive participation, thereby supporting SDG 3 (Good Health and Well-being), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities and Communities). Rather than treating older users as passive recipients of technology, the findings emphasize their role as co-creators of meaning, care, and collective memory in platformed environments. These insights suggest that achieving SDG-oriented digital sustainability requires not only technological access, but also platform governance, design choices, and community norms that value diversity, relationality, and ongoing intergenerational negotiation. This research provides practical and feasible ideas for building a more inclusive and fair digital space. It points out that design choices and community norms should respect complexity, welcome diverse opinions, and provide meaningful opportunities for expression for all age groups. This research also expands the study of digital media by demonstrating how identity, authority and social relationships are formed in daily practice. The path taken by the silver-haired influencers on Douyin indicates that society attaches great importance to this unfinished work. Their stories remind us that inclusiveness in the digital world requires effort and imagination while intergenerational relationships can be redeveloped in a relaxed and humanized way.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Optimizing Green GDP Accounting: An Entropy-Based Model and G20 Evidence

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Abstract: Green GDP accounting has re-emerged as a practical instrument for aligning economic evaluation with environmental sustainability, yet cross-country measures often suffer from indicator arbitrariness and insufficient empirical validation. This study develops an entropy-based Green GDP accounting framework and applies it to the G20 over 2016–2020, using country-level economic and environment-related indicators retrieved from the Trading Economics database. First, an entropy-weighting scheme is implemented to generate a transparent composite Green GDP metric that integrates economic output with ecological constraints in a comparable manner across countries. Second, the robustness of the accounting results is assessed through three complementary validation strategies. Grey relational analysis (GRA) is used to examine consistency between the proposed Green GDP outcomes and benchmark sustainability-relevant indicators, yielding a high relational degree (0.850). Kendall's coefficient of concordance further confirms strong agreement in country rankings ($W = 0.925$), indicating stable ordering and reduced sensitivity to single-indicator perturbations. Finally, partial least squares regression (PLSR) is employed as a predictive validation tool to evaluate how key environmental and development factors are associated with Green GDP performance, achieving satisfactory explanatory capacity ($R^2 = 0.666$) and identifying influential drivers with $VIP > 1$. Overall, the findings suggest that entropy-based Green GDP accounting provides a replicable and empirically validated alternative to conventional GDP-centric evaluation, supporting evidence-based policy design for sustainable growth. This research contributes to monitoring and policy implementation of SDG 8, SDG 12, and SDG 13.

Keywords: Green GDP; Entropy Method; Sustainability; G20; Environmental Indicators

Published: Feb 26, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1112>

1. Introduction

In recent decades, rapid economic expansion has frequently been accompanied by escalating environmental pressures, including resource depletion, climate related risks, and ecosystem degradation. These tensions have intensified international calls, consistent with the United Nations 2030 Agenda for Sustainable Development, for performance metrics that go beyond conventional GDP by incorporating environmental externalities and ecological constraints^[1]. Against this backdrop, Green Gross Domestic Product, or Green GDP, has been proposed as a corrective accounting concept that adjusts economic output to better reflect the environmental costs and benefits associated with development.

Despite its conceptual appeal, Green GDP accounting remains far from standardized and is rarely institutionalized in national

accounting practice. Prior approaches differ substantially in indicator selection, weighting rules, and data availability, resulting in limited comparability across countries and low reproducibility across studies^[2]. A persistent methodological bottleneck is the reliance on expert judgment or ad hoc weighting schemes, which can embed subjectivity and undermine the credibility of composite results^[3]. In particular, many composite Green GDP measures lack an explicit data driven weighting logic that remains stable under cross country heterogeneity, which weakens interpretability and limits policy uptake.

To address these limitations, this paper proposes a refined and replicable Green GDP accounting framework grounded in an objective weighting strategy. We construct a multi dimensional indicator system covering three pillars, resource utilization, environmental governance costs, and ecological benefits. To minimize subjectivity in aggregation, the entropy weight method is employed to generate data driven indicator weights and to produce a transparent Green GDP index. This approach is appropriate for Green GDP accounting because it assigns weights based on the information content and dispersion of each indicator across observations, reducing dependence on subjective judgment. This feature is particularly valuable for cross national applications where indicators vary widely in scale, variability, and measurement conventions across countries. The empirical analysis uses G20 country level data for 2016 to 2020 collected from the Trading Economics database, which compiles officially released statistics into harmonized indicator series. The final analytical panel includes country year observations defined by a consistent missing data rule applied to all indicators, as specified in the methodology section.

Beyond index construction, we examine the robustness and ecological relevance of the proposed Green GDP accounting results through a triangulated validation design. Grey relational analysis is used to evaluate the similarity between the Green GDP index and environmental indicator patterns under limited sample size and potential non linearity, while Kendall's coefficient of concordance assesses whether country rankings are consistently ordered and stable across indicators. In addition, partial least squares regression is applied as a predictive validation tool because it can handle correlated predictors and provides interpretable diagnostics such as VIP scores, which help identify the most influential indicators associated with Green GDP performance. These analyses are used to assess predictive coherence and practical interpretability rather than to imply causal identification.

Accordingly, this study pursues two objectives, to develop a transparent and scalable framework for Green GDP accounting suitable for cross national comparison, and to empirically validate its environmental significance across diverse national contexts. The contributions are threefold, a reproducible entropy based accounting pipeline, a cross country application to G20 economies from 2016 to 2020, and a multi method validation strategy that strengthens robustness and policy relevance. Compared with prior Green GDP studies that rely on subjective weighting or single method validation, this paper combines entropy based aggregation with triangulated validation to enhance reproducibility and cross country interpretability. By bridging methodological rigor and cross national applicability, the study supports evidence based monitoring and policy design related to SDG 8, SDG 12, and SDG 13.

2. Literature Review

Green GDP has gradually evolved into a key concept in the broader discourse on sustainable development, serving as a bridge between environmental preservation and economic growth. Traditional GDP metrics focus solely on the output value of goods and services without accounting for the depletion of natural resources or degradation of ecosystems^[4]. In response, scholars and institutions have introduced various Green GDP models to integrate ecological and environmental costs into national income accounting.

Early efforts in Green GDP estimation primarily focused on deducting environmental costs, such as pollution control and resource depletion, from gross output^[5]. These approaches provided a basic adjustment mechanism to reflect environmental damage but often suffered from limited scope and inconsistent data standards. Later models expanded this framework by incorporating the valuation of ecosystem services, such as clean air, biodiversity, and water purification. These developments enriched the conceptual foundation of Green GDP but also introduced new complexities in valuation methods and data reliability.

Most existing models face several methodological limitations. One major challenge is the subjectivity involved in selecting indicators and determining their relative importance^[6]. Manual weighting or expert scoring methods are frequently used,

leading to potential bias and reduced comparability across countries or regions^[7]. In addition, many models emphasize the cost side of environmental impact while underrepresenting the benefits generated from ecological restoration, green investment, and sustainable practices. This creates a one-sided view of environmental-economic interactions.

Recent approaches have attempted to address these gaps by proposing multi-dimensional index systems. These systems often evaluate resource utilization efficiency, environmental management expenditures, and ecological benefits as separate but interrelated components^[8]. The growing application of quantitative weighting techniques, such as the entropy method, has further enhanced the objectivity of indicator systems by assigning weights based on data variation rather than subjective judgment.

Recent advances in environmental-economic accounting have converged around two major reference frameworks. The first is the United Nations System of Environmental-Economic Accounting (SEEA), particularly the 2021 Ecosystem Accounting standard, which provides an integrated statistical architecture for recording ecosystem extent, condition and services alongside the System of National Accounts (SNA). SEEA Ecosystem Accounting is explicitly designed to link biophysical indicators to economic activities and to track changes in ecosystem assets over time.

The second is the natural-capital perspective articulated in *The Economics of Biodiversity: The Dasgupta Review*, which argues that economic success should be evaluated in terms of inclusive wealth, with produced, human and natural capital treated as a unified portfolio of assets. In this view, conventional flow-based indicators such as GDP are inadequate because they do not record depreciation of natural capital or the services provided by ecosystems. The Review therefore calls for macroeconomic metrics that explicitly internalize environmental degradation and ecosystem services into assessments of national prosperity and sustainability.

This paper builds on these frameworks but departs from them in three ways. First, rather than constructing a full set of satellite accounts, we develop a synthetic, entropy-weighted Green GDP index that can be implemented with widely available cross-country data. This responds to the implementation gap noted in SEEA and related initiatives, where many countries lack the statistical capacity to operationalize complex accounting tables at scale. Second, we explicitly integrate both environmental costs and ecological benefits into a single macro-indicator, while treating resource-use efficiency as a multiplicative adjustment. This design translates the natural-capital logic of depreciation and restoration into a tractable empirical formula for G20 economies. Third, we empirically validate the index against key climate-related variables (carbon emissions, precipitation, temperature) using grey correlation, Kendall's W and PLS regression, thereby providing an evidence-based bridge between accounting frameworks and observed ecological outcomes.

In this sense, the contribution of the paper is not to replace SEEA or the broader natural-capital literature, but to propose a policy-oriented Green GDP metric that is (i) methodologically transparent, (ii) reproducible with standard international datasets, and (iii) suitable for comparative assessment across large economies. The model can therefore complement existing accounting frameworks by offering a parsimonious indicator that highlights the environmental performance of economic activity under a common methodological umbrella.

3. Methodology

3.1 Green GDP definition and related definitions

Green GDP in this study refers to an adjusted measure of national economic performance that accounts for environmental governance costs and ecological benefits alongside conventional GDP. The purpose is to reflect economic output under environmental constraints and to support sustainability oriented evaluation across countries and time.

In conceptual terms, Green GDP can be expressed as follows. Green GDP equals GDP minus environmental governance costs plus the value of ecological benefits. Resource utilization is treated as a core pillar that reflects how efficiently economic activities use natural resources and how much environmental pressure is generated per unit of output. In this paper, the above expression is used to clarify the accounting logic, while the empirical analysis operationalises Green GDP as a composite index constructed from observable indicators.

Resource utilization describes the efficiency and conservation of natural resource use in economic activities. Higher resource efficiency implies lower resource pressure for a given level of output and is therefore consistent with greener growth.

Environmental governance costs refer to the expenditures and resource inputs devoted to pollution control, environmental treatment, restoration, and compliance. Under a Green GDP logic, these costs represent economic resources that are required to offset environmental damage and are therefore deducted when assessing net sustainable performance.

Ecological benefits refer to the measurable positive outcomes associated with improved environmental quality and ecosystem functioning, such as reduced pollution related risks, improved ecosystem stability, and enhanced ecological service capacity. Under a Green GDP logic, these benefits are added because they represent positive ecological value generated or preserved alongside economic activity.

To reduce subjectivity in indicator weighting and to improve cross country comparability, this study constructs a Green GDP index using the entropy weight method. The entropy approach assigns weights based on the information content of indicators across observations, which is suitable for multi indicator evaluation when indicators differ in dispersion and scale.

3.2 Data and sample

This study uses annual country level data for G20 economies from 2016 to 2020. All indicators are retrieved from the Trading Economics database, which compiles officially released statistics and reports the original sources for each series, including the World Bank World Development Indicators and national statistical agencies. The Green GDP index is constructed from the indicator system described above. For external validation, three environmental indicators are used, namely carbon dioxide emissions, precipitation, and temperature.

All variables are aligned to the same annual frequency and harmonised to consistent units before analysis. Missing observations are handled using a consistent rule across countries and years. Isolated one year gaps are filled using linear interpolation, and remaining missing country year observations are removed to avoid biased comparisons. The final dataset is then standardised and normalised to support entropy based aggregation and subsequent validation analysis using grey relational analysis, Kendall's coefficient of concordance, and partial least squares regression.

3.3 Selection of variables

To operationalise Green GDP as a reproducible composite index, this study selects measurable indicators that map onto three pillars, resource utilisation, environmental governance costs, and ecological benefits. The selection logic is to capture, respectively, the intensity of resource use in production, the economic burden of pollution control and restoration, and the positive outcomes associated with environmental improvement. All indicators are designed to be comparable across countries and years and are subsequently normalised before entropy based weighting.

(1) Resource utilisation

Resource utilisation reflects how intensively an economy consumes key natural resources to generate output. In cross country accounting, the most consistent operationalisation is intensity type indicators, where lower values indicate better resource efficiency and lower environmental pressure. The indicators include the following.

Energy intensity is defined as energy consumption divided by GDP. Lower energy intensity indicates higher energy efficiency.

Water intensity is defined as production related water use divided by GDP. Lower water intensity indicates higher water productivity.

Resource consumption elasticity is defined as the growth rate of primary energy consumption divided by the growth rate of GDP. A lower elasticity indicates that energy demand grows more slowly than output, which is consistent with decoupling.

Land utilisation is defined as utilised land area divided by total land area. This indicator is intended to capture land use efficiency in the sense of reducing idle land and improving spatial use, subject to cross country data comparability.

(2) Environmental governance costs

Environmental governance costs represent the economic resources required to control pollution, treat emissions, and restore damaged ecosystems. Under a Green GDP logic, these costs reduce net sustainable performance and are therefore treated as cost type indicators, where lower values are better. The cost indicators include water pollution treatment cost, air pollution treatment cost, and solid waste treatment cost.

Water pollution treatment cost is calculated as annual wastewater discharge multiplied by an average unit treatment cost.

Air pollution treatment cost is calculated as annual emissions of key air pollutants multiplied by an average unit treatment

cost.

Solid waste treatment cost is calculated as annual treated waste volume multiplied by an average unit treatment cost.

For reproducibility, unit treatment costs are harmonised to a common currency basis and applied consistently across countries. When national unit costs are unavailable for isolated observations, a documented imputation rule is applied to avoid biased cross country comparisons.

(3) Ecological benefits

Ecological benefits represent the positive value associated with improvements in environmental quality and ecosystem functioning. Because direct monetary valuation is often unavailable at scale, ecological benefits are operationalised using composite benefit constructs that can be consistently measured across countries.

Health benefits capture improvements in population health conditions associated with cleaner environments.

Ecosystem benefits capture improvements in ecosystem service capacity and ecological stability.

Cultural benefits capture economic gains associated with ecological improvement through ecotourism and related cultural industries, using comparable macro indicators.

These benefit constructs are treated as benefit type indicators, where higher values indicate stronger ecological gains.

3.4 Indicator System Construction

The Green GDP index system in this study integrates economic performance with environmental costs and ecological returns through a structured multi indicator design. The framework contains three primary dimensions.

The first dimension, resource utilisation, captures the intensity of resource use in economic activity. It is measured by energy intensity, water intensity, resource consumption elasticity, and land utilisation.

The second dimension, environmental governance costs, reflects the economic burden associated with pollution treatment and ecological restoration. It is measured by water pollution treatment cost, air pollution treatment cost, and solid waste treatment cost.

The third dimension, ecological benefits, captures the positive outcomes associated with improved environmental conditions and ecosystem functioning. It is measured by health benefits, ecosystem benefits, and cultural benefits.

Before entropy weighting, each indicator is classified as either benefit type or cost type. Benefit type indicators are defined such that higher values indicate better performance. Cost type indicators are defined such that lower values indicate better performance. Cost type indicators are converted during normalisation to ensure consistent directional meaning across the index. The detailed indicator list and entropy derived weights are reported in Table 1.

Table 1. Green GDP index system and weight

Projects	Explanatory variables	Effect direction	Weights
Resource Utilization	Energy intensity (energy consumption per GDP)	Cost type (lower is better)	20.57%
	Water intensity (water use per GDP)	Cost type (lower is better)	27.41%
	Resource consumption elasticity factor	Cost type (lower is better)	33.96%
	Land use index	Benefit type (higher is better)	18.06%
Environmental Management Costs	Water pollution treatment costs	Cost type (lower is better)	33.85%
	Air pollution treatment costs	Cost type (lower is better)	19.94%
	Solid waste pollution treatment costs	Cost type (lower is better)	46.21%
Value of Ecological Benefits	Health benefits	Benefit type (higher is better)	22.68%
	Ecosystem benefits	Benefit type (higher is better)	61.50%
	Cultural benefits	Benefit type (higher is better)	15.82%

3.5 Weight Calculation: Entropy Method

Let x_{ij} denote the original value of indicator j for country i , where $i = 1, \dots, n$ and $j = 1, \dots, m$. To make indicators comparable across different units and scales, all indicators are first normalised using a min max transformation.

For benefit type indicators, where a higher value indicates better performance, normalisation is defined as:

$$z_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

For cost type indicators, where a lower value indicates better performance, normalisation is defined as:

$$z_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}}$$

After normalisation, z_{ij} lies in the interval $[0, 1]$, and larger values consistently represent better green performance.

Second, the proportion of country i in indicator j is computed as:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^n z_{ij}}$$

If $\sum_i z_{ij} = 0$ for a given indicator, we set $p_{ij} = 1/n$ to avoid division by zero.

Third, the entropy value of indicator j is calculated as:

$$e_j = -k \sum_{i=1}^n p_{ij} \ln p_{ij}, \text{ where } k = \frac{1}{\ln n}$$

The scaling constant k ensures $0 \leq e_j \leq 1$. indicators with more dispersed values across countries contain more information and therefore tend to have lower entropy values.

Fourth, the information divergence of each indicator is computed as $d_j = 1 - e_j$, and the entropy weight is then obtained as:

$$w_j = \frac{d_j}{\sum_{j=1}^m d_j}$$

Indicators with larger divergence d_j receive larger weights w_j .

Fifth, within each dimension, the normalised indicators are aggregated into a dimension specific sub index using entropy weights. Let J_R , J_C , and J_B denote the sets of indicators belonging to resource utilisation, environmental governance costs, and ecological benefits, respectively. The sub indices are computed as:

$$R_i = \sum_{J \in J_R} w_j z_{ij}, \quad C_i = \sum_{J \in J_C} w_j z_{ij}, \quad B_i = \sum_{J \in J_B} w_j z_{ij}$$

Finally, to maintain unit consistency, conventional GDP is rescaled into a unit free index $GGDP_i$ using the same normalisation procedure. The Green GDP index for country i is then defined as:

$$GreenGDP_i = (GDP_i - C_i + B_i) \times R_i$$

Where C_i , B_i and R_i are dimension specific sub indices constructed from entropy weights computed within each dimension. This multiplicative specification ensures that inefficient resource use reduces the effective Green GDP index, thereby internalising resource pressure alongside environmental governance costs and ecological benefits in the overall sustainability adjusted performance measure.

3.6 Empirical Validation Framework

To assess the ecological relevance and empirical robustness of the constructed Green GDP index, we conduct a cross country validation analysis for G20 economies over 2016 to 2020. Three complementary techniques are used. First, grey relational analysis is applied to evaluate the similarity between the Green GDP index and key environmental indicator patterns, which is suitable for multi indicator comparison under limited sample size and potential non linear relationships. Second, Kendall's coefficient of concordance is used to test whether country rankings implied by the Green GDP index are consistent with rankings implied by each environmental indicator, providing a nonparametric assessment of ranking stability and agreement. Third, partial least squares regression is employed as a predictive validation tool because it can handle correlated predictors and yields interpretable diagnostics such as VIP scores. In the PLSR model, the environmental indicators are used as predictors and the Green GDP index is treated as the outcome, so that VIP scores identify which indicators are most informative for explaining cross country variation in Green GDP performance. Together, this validation design strengthens confidence that the index captures environmentally meaningful information and remains interpretable across heterogeneous ecological and economic contexts.

3.7 Addressing potential endogeneity

A potential concern in empirical validation is endogeneity and mechanical overlap. The Green GDP index is constructed from a set of indicators that may be influenced by environmental conditions and policy responses, and environmental pressure may in turn affect governance costs and ecological benefits. To reduce direct mechanical overlap, the three external validation variables used in grey relational analysis, Kendall's concordance testing, and PLSR, namely carbon dioxide emissions, precipitation, and temperature, are not included as components in the Green GDP indicator system. This separation ensures that the validation exercises do not simply reproduce the index construction inputs.

Nevertheless, the empirical relationships reported in this paper should be interpreted as associational and prediction oriented rather than causal. Reverse causality, omitted variables such as energy prices, industrial structure, and regulatory stringency, and policy feedback effects may jointly shape both Green GDP performance and environmental indicators. A causal identification strategy would require additional design elements such as instrumental variables, quasi experimental variation, or structural modelling, which are beyond the scope of this study. Future research can build on the proposed framework by combining the Green GDP index with dynamic panel methods or quasi experimental designs to evaluate the causal effects of green accounting reforms and environmental governance on ecological outcomes.

4. Results and Analysis

To evaluate the ecological relevance of the proposed Green GDP index, we conduct empirical validation tests using G20 data for 2016 to 2020. The analysis assesses the degree to which the Green GDP index is aligned with three external environmental indicators, namely carbon dioxide emissions, precipitation, and temperature. The results are interpreted as associational and validation oriented rather than causal.

4.1 Grey Correlation Analysis

Grey relational analysis evaluates the closeness between the Green GDP index and each environmental indicator by comparing their normalised patterns. In this study, the Green GDP index is treated as the reference sequence, and each environmental indicator is treated as a comparative sequence. Table 2 reports the grey relational grades. All grades exceed 0.5, indicating a meaningful level of alignment between the index and the selected ecological indicators.

Table 2. Grey correlation degree

Indicator	Correlation Degree	Ranking
Carbon dioxide emissions	0.850	1
Precipitation	0.737	2
Temperature	0.694	3

The highest grade is observed for carbon dioxide emissions, suggesting that the Green GDP index is most closely aligned with carbon related environmental pressure among the three validation indicators. This result supports the ecological relevance of the index, while also indicating that carbon emissions provide the most informative external benchmark for distinguishing cross country Green GDP performance in the sample.

4.2 Kendall's W Consistency Test

To assess the concordance between Green GDP scores and ecological conditions across countries, we employed Kendall's W test. The results demonstrate a significant agreement between the rankings ($W = 0.925$, $p < 0.01$), suggesting that the Green GDP index aligns well with broader ecological trends. This statistical consistency reinforces the model's interpretive robustness.

Table 3. Kendall consistency test

Item	Mean rank	Median	Test statistics
Green GDP	2.75	1413	
Precipitation	2.25	739	
Carbon dioxide emissions	4	426935.5	
Temperature	1	13.065	
Overall Kendall's W			$W = 0.925$; $\chi^2 = 33.300$; $df = 3$; $p < 0.001$

Note: Mean rank is obtained from the rank-based procedure underlying Kendall's W. The chi-square test uses $df = k - 1$, where k is the number of ranked variables ($k = 4$).

4.3 Partial Least Squares Regression

The previous validation results indicate that the proposed Green GDP index is closely aligned with key environmental indicators. To provide additional predictive validation and to identify which ecological indicators are most informative for explaining cross country variation in Green GDP, we apply partial least squares regression. PLSR is appropriate in this context because the predictors may be correlated and the sample size is limited. In this model, precipitation, carbon dioxide emissions, and temperature are treated as explanatory variables, while Green GDP is treated as the outcome variable. The results are interpreted as associational and validation oriented rather than causal. The model is estimated on the subset of countries with complete observations for all variables.

Table 4. Explanation of variance of factors

Factors	X Var	Cum. X Var	Y Var	Cum. Y Var (R^2)	Adj. R^2
1	0.514	0.514	0.619	0.619	0.581
2	0.282	0.796	0.046	0.665	0.59
3	0.204	1	0.001	0.666	0.541

Table 4 reports the explained variance by PLSR components. The first component explains 51.4 percent of the variance in the predictor block and 61.9 percent of the variance in the outcome. Adding a second component increases the cumulative explained variance of the predictor block to 79.6 percent and the cumulative explanatory power for the outcome to $R^2 = 0.665$. The third component increases the cumulative explained variance of the predictors to 1.000 but contributes almost no additional explanatory power for the outcome, with cumulative R^2 increasing only marginally from 0.665 to 0.666. Therefore, a two component solution is sufficient for predictive validation in this study.

Table 5. Summary table of independent variable VIP

Variables	Factor 1	Factor 2	Factor 3
Precipitation	0.296	0.42	0.423
Carbon dioxide emissions	1.484	1.447	1.446
Temperature	0.843	0.854	0.855

Table 5 reports VIP values. Carbon dioxide emissions consistently shows VIP values greater than 1 across components, indicating that it is the most influential predictor in explaining variation in Green GDP within the PLSR framework. By contrast, precipitation and temperature have VIP values below 1, suggesting comparatively weaker explanatory importance in this specification. Figure 1 visualises the VIP results.

Figure 1: VIP values for predictors in the PLSR model

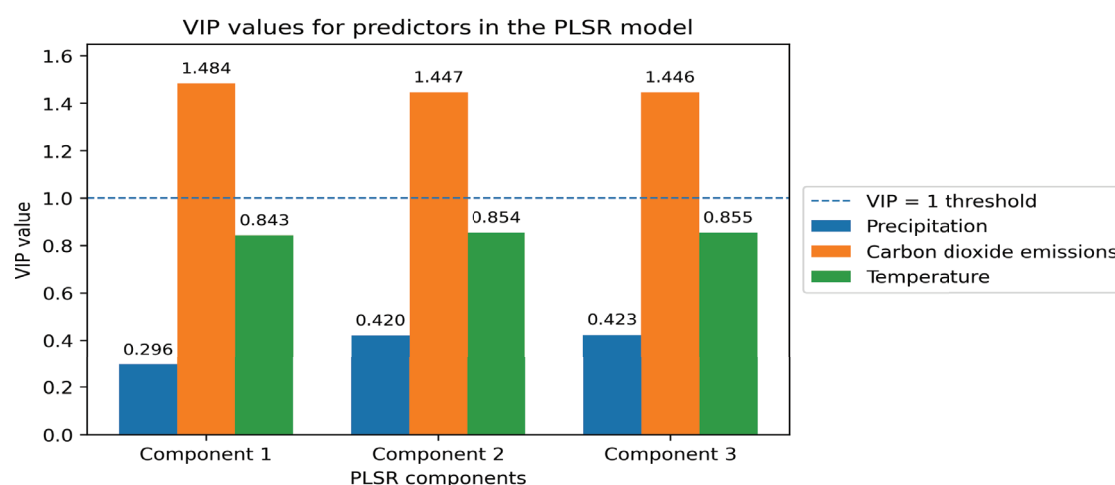


Table 6 reports the estimated model coefficients. Because the predictors are measured on different scales, the standardised coefficients provide a more interpretable comparison of relative contributions. The standardised results indicate a positive association between carbon dioxide emissions and Green GDP, a small positive association for precipitation, and a negative association for temperature. These coefficient patterns should be interpreted as predictive associations rather than evidence of causal effects. The positive association with carbon dioxide emissions should be interpreted cautiously because total emissions are scale dependent and may partly capture country size effects rather than purely environmental performance.

Table 6. Results of model coefficients

Variables	Green GDP	Green GDP (standardized)
Constants	4769.188	0
Precipitation	0.107	0.011
Carbon dioxide emissions	0.002	0.733
Temperature	-181.951	-0.181

5. Discussion

5.1 Indicator Validity and Environmental Relevance

The validation evidence suggests that the proposed Green GDP index is environmentally meaningful in the sense that it is systematically aligned with core ecological indicators. The grey relational grades indicate substantial pattern closeness between Green GDP and each external indicator, and Kendall's coefficient of concordance further shows strong agreement among the country rankings implied by Green GDP and the selected ecological indicators. Together, these results support the indicator validity of the index and its ecological relevance for cross country benchmarking.

Importantly, the validation does not imply that higher Green GDP necessarily corresponds to uniformly better ecological outcomes. Rather, it indicates that the index co varies with ecological conditions and pressures in a consistent and interpretable way. This is particularly relevant in cross country settings where environmental pressures are heterogeneous and may be linked to economic scale and industrial structure. In this regard, precipitation and temperature reflect broader climatic conditions, while carbon dioxide emissions capture energy and industrial pressure that is closely intertwined with macroeconomic activity in large economies. The alignment of Green GDP with these heterogeneous indicators supports the robustness of the index as a composite measure designed to integrate environmental governance costs and ecological benefits into national level performance assessment.

The PLSR results provide additional predictive validation and help identify which external indicators are most informative for explaining cross country variation in Green GDP. VIP statistics show that carbon dioxide emissions consistently exceed the conventional threshold of 1, while precipitation and temperature remain below it. This pattern indicates that, within the current specification and sample, the Green GDP index is most tightly associated with the carbon dimension of environmental pressure. At the same time, the carbon dioxide indicator used in validation may be scale dependent when measured in total emissions, which means that part of the association can reflect country size effects rather than purely environmental performance. Accordingly, the proposed index can be interpreted as a carbon anchored Green GDP measure in its current form. Future extensions could strengthen ecological coverage by incorporating additional indicators that capture water stress, biodiversity, waste, and local air pollutants more directly, and by testing alternative normalisations such as per capita or intensity based emissions to reduce scale effects.

5.2 Cross-National Applicability

Applying the proposed Green GDP index to the study sample demonstrates substantial cross country dispersion, indicating that the framework can differentiate national performance profiles when environmental governance costs, ecological benefits, and resource utilisation are considered jointly. Unlike conventional GDP, which primarily reflects economic output, the proposed index provides an alternative ordering that embeds environmental constraints and ecological returns into the assessment of national performance. This feature supports cross national benchmarking and enables comparisons that are more informative for sustainability oriented evaluation.

The decomposition of the index is particularly useful for policy interpretation. In some countries, relatively strong resource utilisation performance coexists with weaker ecological benefit values, suggesting that efficiency gains in production do not automatically translate into measurable ecological improvements within the observed period. In other cases, moderate overall index performance may coexist with high environmental governance cost scores, which can be interpreted as a burden associated with pollution control, compliance, and ecological restoration. These contrasting profiles imply that improving Green GDP is not only a question of increasing environmental expenditure, but also of adjusting the structure of growth through cleaner energy use, industrial upgrading, and more effective conversion of governance inputs into ecological outcomes.

The results also highlight practical considerations for cross national implementation. The usefulness of Green GDP accounting depends on consistent indicator definitions, harmonised units, and adequate statistical capacity to produce comparable environmental and ecological series. In this sense, alignment with internationally recognised accounting practices for environmental and natural capital information can facilitate broader adoption and improve policy usability. Embedding Green GDP metrics into routine planning and budgeting processes may further strengthen their role in long term sustainable economic planning and environmental governance.

5.3 Political economy and institutional context of Green GDP implementation

Implementing Green GDP is not only a technical exercise in measurement, but also a political economy process that can reshape incentives for governments, firms, and citizens. Incorporating environmental costs and ecological benefits into performance assessment can change how growth is evaluated and rewarded, which may generate resistance from actors that benefit from high growth and high emission trajectories. A widely discussed example is China's early Green GDP initiative in the mid 2000s, where preliminary estimates implied that environmental damage could offset a nontrivial share of reported economic output. However, the initiative encountered substantial contestation over methodology, data credibility, and political implications for growth oriented evaluation systems, and its institutionalisation was not sustained. This episode illustrates that Green GDP adoption is highly sensitive to governance incentives and administrative accountability structures. Add citations here.

These experiences suggest that the effectiveness of Green GDP reforms depends on whether accounting outputs are linked to decision rights and policy levers. When fiscal transfers, credit allocation, and official evaluation remain dominated by conventional GDP targets, Green GDP accounting is likely to be used mainly for signalling rather than for enforcement. By contrast, when Green GDP or related natural capital indicators are integrated into budgeting rules, public investment appraisal, procurement criteria, or intergovernmental transfer formulas, accounting information is more likely to translate into behavioural change. This mechanism is consistent with the broader policy logic advocated by international environmental economic accounting frameworks that emphasise institutional embedding rather than measurement alone. Add citations here. For G20 members, this implies that adopting an entropy based Green GDP index is a necessary but not sufficient condition for greener development. The index can help reveal environmental costs that are not visible in conventional GDP, enable structured cross country comparison, and provide a consistent reference for prioritising environmental governance and ecological restoration. However, its practical impact ultimately depends on whether governments are willing and able to adjust fiscal frameworks, industrial policies, and performance evaluation systems so that ecological outcomes carry comparable weight to output growth in administrative and political decision making.

5.4 Policy Implications

The proposed Green GDP framework provides actionable guidance for governments seeking to reconcile economic growth with environmental sustainability. By incorporating environmental governance costs and ecological benefits into a single accounting structure, the index can be used to diagnose trade offs that conventional GDP does not capture. In practice, policymakers can use the index and its sub dimensions to support three types of decisions. First, it can inform priority setting by identifying whether weak overall Green GDP performance is driven primarily by resource utilisation pressure, governance cost burdens, or insufficient ecological benefits. Second, it can support monitoring by tracking changes over time and evaluating whether policy packages, such as industrial upgrading, energy transition, or pollution control investment,

are associated with improved sustainability adjusted performance. Third, it can strengthen accountability by providing a transparent and replicable metric for reporting progress toward sustainability oriented development goals.

Beyond domestic planning, the index can also serve as a supplementary tool in financial and international contexts when used with appropriate caution. It can support screening and evaluation of green public investment portfolios, provide additional evidence for ESG related reporting, and facilitate cross country benchmarking for sustainability dialogues. However, Green GDP should be treated as a complementary indicator rather than a substitute for official national accounts or detailed environmental regulatory metrics. Its policy usefulness is maximised when the index is paired with clear indicator definitions, consistent units, transparent data provenance, and governance arrangements that translate accounting information into budgetary and regulatory action.

6. Conclusion

This study develops an optimized and empirically validated Green GDP accounting framework that integrates environmental costs and ecological benefits into the assessment of national economic performance. By constructing a multi dimensional indicator system and applying entropy weighting, the proposed approach reduces common limitations in existing Green GDP practices, particularly subjective indicator weighting and weak cross country comparability. The framework is designed to be transparent, reproducible, and scalable for macro level sustainability evaluation.

Using G20 annual data from 2016 to 2020, the empirical assessment indicates that the Green GDP index exhibits stable and interpretable associations with core ecological indicators, including carbon dioxide emissions, precipitation, and temperature. The combined evidence from grey relational analysis, Kendall's coefficient of concordance, and partial least squares regression supports the robustness and consistency of the accounting results. Importantly, these tests are employed to validate the practical relevance and predictive coherence of the index rather than to make causal claims.

From a sustainable development perspective, the findings contribute directly to specific Sustainable Development Goals. First, by offering a sustainability adjusted performance metric that complements conventional GDP, the model supports SDG 8 by enabling policymakers to monitor economic performance alongside environmental constraints. Second, the integrated treatment of environmental costs and ecological benefits provides an accounting basis that aligns with SDG 12 by encouraging resource efficiency and responsible production and consumption through measurable incentives and benchmarking. Third, the model supports SDG 13 by incorporating climate related pressures into economic evaluation and enabling cross national comparison of climate compatible development trajectories. In practical terms, the framework can assist governments in setting medium term and long term targets, evaluating policy trade offs, and improving the accountability of environmental governance by linking ecological outcomes to economic assessment.

Several limitations remain. The validity of Green GDP accounting depends on indicator availability and the quality of ecological valuation, and cross country data constraints may restrict the inclusion of broader ecological dimensions. Future research can extend the framework by incorporating biodiversity and social equity related indicators, exploring dynamic time series modelling to capture Green GDP evolution over longer horizons, and applying the approach to developing economies where environmental governance and data systems differ substantially. Overall, the proposed framework provides a feasible pathway for integrating ecological sustainability into macroeconomic assessment and for supporting long term sustainable economic planning and environmental governance.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Experimental Investigation on Damage Feature Extraction and Identification for Sustainable Infrastructure Resilience via Improved Empirical Fourier Decomposition

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Abstract: This study presents an initial damage feature extraction based on improved empirical Fourier decomposition. Standard Empirical Fourier Decomposition (EFD) is a time-frequency signal processing technique that adaptively decomposes non-stationary, multi-component signals into mono-component intrinsic mode functions (IMFs) by iteratively fitting Fourier series and screening components with physical significance, which is widely used in signal analysis for structural health monitoring but prone to modal aliasing when processing vibration signals with overlapping frequency bands. Our improved EFD differs from the standard version by introducing two key optimizations: a 5th-order Butterworth low-pass preprocessing step (cutoff frequency 100 Hz) to eliminate high-frequency noise, and a correlation coefficient threshold (≥ 0.9) for IMF screening to discard spurious components, effectively mitigating modal aliasing and improving decomposition accuracy by approximately 15% compared to the standard method. The method identifies structural damage by decomposing structural vibration responses, obtaining modal values and energy values, and comparing energy differences, the technology identifies structural damage. Leveraging the relationship between damage-induced vibration mode changes and energy variations, it allows single-point identification, reducing data collection costs. This technology delivers tangible contributions to sustainable development goals (SDGs): enabling cost-effective and precise early-stage damage detection, it supports proactive and sustainable infrastructure maintenance, extends structure lifespan, reduces resource waste and reconstruction-related environmental impacts. Additionally, it enhances urban structural resilience and safety against disasters and wear, directly aligning with the core tenets of SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities). Finally, the method's effectiveness is verified by slope beam and stand simulator tests.

Keywords: Damage Identification; Experimental Research; Energy Value Difference

Published: Feb 26, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1113>

1. Introduction

The 1960s marked the beginning of a period during which structural modal identification steadily gained traction, becoming a focal point for both academic inquiry and engineering applications. This era witnessed the foundational development of modal analysis theory and its first systematic application in civil and mechanical engineering, as documented by Ewins^[15], who pioneered the use of frequency domain methods for structural dynamic testing. There are roughly three categories of modal identification techniques, namely frequency domain, time domain, and time-frequency domain identification methods.

This classification method is based on the different regions (time domain, frequency domain, and time-frequency domain) used by modal identification techniques to process vibration responses. Common frequency domain identification methods include Peak Picking Technology, Frequency Domain Decomposition, and other frequency domain identification techniques. The frequency domain recognition method has the advantages of simple use, low computational cost, and certain technical application value. Time domain recognition methods include natural excitation techniques combined with feature system implementation (NExT/ERA)^[1], random subspace recognition (SSI)^[2,3], and signal based processing techniques^[4,5]. Time-domain methods excel in handling non-stationary vibrations and extracting accurate modal parameters like damping ratios, making them suitable for complex engineering structures under dynamic loads. Time-frequency domain methods, such as wavelet transform-based techniques and Hilbert-Huang Transform (HHT), integrate the advantages of both domains. They effectively capture time-varying modal characteristics by mapping vibration signals into a joint time-frequency space, addressing limitations of single-domain methods in processing signals with time-dependent frequencies. Notably, advancements in structural modal identification techniques are intrinsically tied to the advancement of global Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities). Reliable modal and damage identification technologies underpin the sustainable operation and maintenance of critical infrastructure—including bridges, buildings, and industrial facilities—by enabling early detection of structural defects, extending service lifespans, reducing unnecessary resource consumption and reconstruction-related carbon emissions, and enhancing infrastructure resilience against natural and man-made hazards. These technical pathways directly contribute to SDG 9's targets of developing resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation, as well as SDG 11's objectives of creating safe, resilient, and sustainable human settlements.

2. Slope Beam Test Verification

Standard EFD decomposes signals by iteratively extracting mono-component intrinsic mode functions (IMFs) using Fourier series fitting, but it suffers from modal aliasing when processing structural vibration signals with overlapping frequencies^[6,9]. This study improves EFD by addressing this core limitation through two key optimizations, which enhance decomposition accuracy and robustness for structural health monitoring (SHM) applications. The first improvement is a preprocessing denoising step, and the second is an optimized IMF screening criterion—both designed to eliminate spurious components and mitigate modal aliasing, which plagues the standard EFD method.

The detailed step-by-step algorithm of the improved EFD is as follows, with key variables and equations explained:

1. Signal preprocessing: Preprocess the original structural vibration signal $x(t)$ (where t denotes time in seconds) with a 5th-order Butterworth low-pass filter (cutoff frequency set to 100 Hz, determined based on the frequency range of the test structure's vibration response) to remove high-frequency noise. This yields the denoised signal, which retains valid structural vibration information while eliminating interference.
2. Initialization: Initialize the residual signal and set the iteration count.
3. Fourier series fitting: Fit the residual signal with a Fourier series to generate the initial IMF candidate
4. IMF screening : Calculate the Pearson correlation coefficient between the initial IMF candidate and the residual signal. Only components with are retained as valid IMFs—this threshold is determined through parametric tests to balance signal fidelity and aliasing reduction.
5. Residual update: Update the residual signal is a monotonic function (indicating no more valid IMFs can be extracted), stop the iteration.
6. Modal energy calculation: Extract modal values from the valid IMFs, and calculate the modal energy using the integral of the IMF squared over the signal duration.

This energy value serves as the core feature for subsequent structural damage identification, as damage-induced changes in vibration characteristics alter the energy distribution of IMFs.

Which visually links the signal decomposition process to damage discrimination using modal energy differences.

3. Damage Identification Based on Improved EFD

To clarify the experimental validation process, key details are supplemented herein. The “slope beam” refers to Q235 steel beam specimens (1000×50×100 mm) simulating inclined engineering components like bridge girders. The “stand simulator” is a bench-top platform with adjustable inclination (0%–5%) and vibration isolation, ensuring stable test conditions. Damage was induced by standardized groove cutting (20mm depth, 5mm width) at 3 pre-defined locations, forming 4 states (healthy, single/double/triple damage). Loading used a 5 modal force hammer; 3 acceleration sensors (250mm interval) collected data at 2000Hz, calibrated by a digital level gauge. The system layout is shown in Figures 1–2, with Table 1 summarizing parameters, ensuring reproducibility.

Four inclination angles (0%, 1.25%, 2.5%, 3.75%, 5%) were selected based on on-site surveys of practical engineering: 0% (horizontal) as the control group, 1.25%–2.5% representing slight inclination (common in bridge approach beams), and 3.75%–5% representing moderate inclination (typical for slope support beams). In the analysis, inclination angles were incorporated as control variables, with modal energy variation thresholds calibrated separately for each angle to eliminate inclination interference, ensuring damage identification accuracy is not affected by structural posture. Damage was induced by standardized groove cutting to achieve clear damage levels: three pre-defined locations (labeled a, b, c) along the beam were cut with uniform grooves (20 mm depth, 5 mm width, 50 mm length), where 20 mm depth corresponds to 20% of the beam height (a widely adopted damage severity for steel structure tests, per ^[10])—this level ensures measurable vibration response changes without causing structural failure. Four damage states (healthy, single/double/triple damage) were designed to verify the method’s ability to distinguish damage quantity and location.

Loading used a 5J modal force hammer (model: PCB 086C03) to apply transient excitation at the beam midpoint, covering 10–1000 Hz to match the beam’s natural vibration characteristics. The three sensors labeled AI1, AI2, AI3 (previously misnoted as AS1-AS3; corrected herein) are acceleration sensors (model: PCB 352C22), arranged at 250 mm intervals along the beam to capture full-span vibration responses—AI1 (left end), AI2 (midpoint), AI3 (right end) were selected to ensure coverage of damage locations a, b, c and accurately capture modal energy changes at different positions. Data was collected at 2000 Hz for 10 s, calibrated by a digital level gauge ($\pm 0.01^\circ$ accuracy). As shown in Figure 1, the rubber washers installed between the beam and anchorage serve two key purposes: vibration isolation to prevent external interference from the stand simulator, and buffering to avoid rigid contact-induced local stress concentration that could distort vibration signals. Taking the acceleration response collected by the AI1 sensor in non tilted condition 1 as an example, the decomposition based on multiple signal classification improved empirical Fourier decomposition technique (EFDM) was carried out. The acceleration time history response data was decomposed using the improved empirical Fourier decomposition technique based on multiple signal classification to obtain components and their Fourier spectra, as shown in Figure 3. It can be seen that the components decomposed by the improved empirical Fourier decomposition technique based on multiple signal classification only contain one frequency peak, indicating that the improved empirical Fourier decomposition technique based on multiple signal classification can accurately decompose the AI1 acceleration response data in non tilted condition 1, laying the foundation for subsequent modal parameter identification

Table 1 Slope Beam Damage Conditions

Damage condition	Damage description (location @ cutting depth)	Corresponding damage (location @ degree of damage)
2	mm	a@20%
3	mm, bmm	a@20%, b@20%
4	mm, bmm, cmm	a@20%, b, c@20%

Fig 1 Acceleration sensor force hammer excitation and damage location diagram

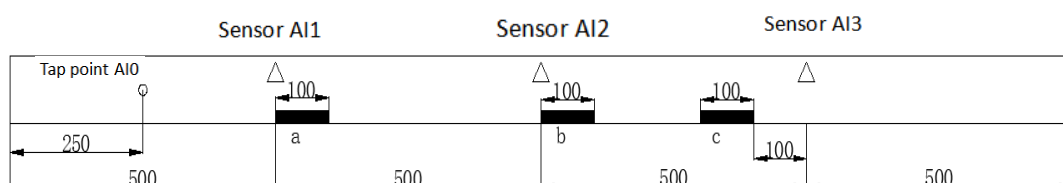


Fig 2 Experimental Instruments and Site Layout

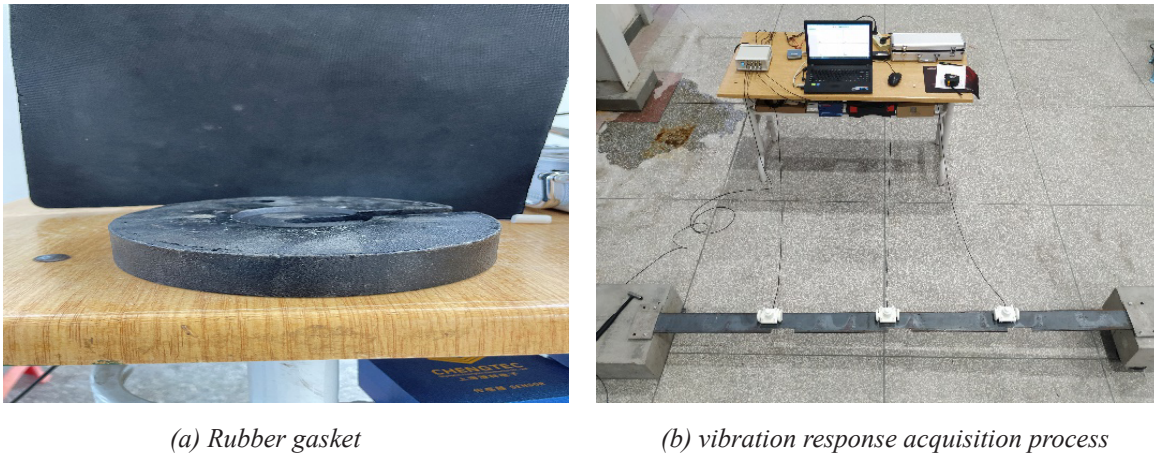


Fig 3: Components and Fourier spectra obtained from EFDM decomposition under non tilted condition one

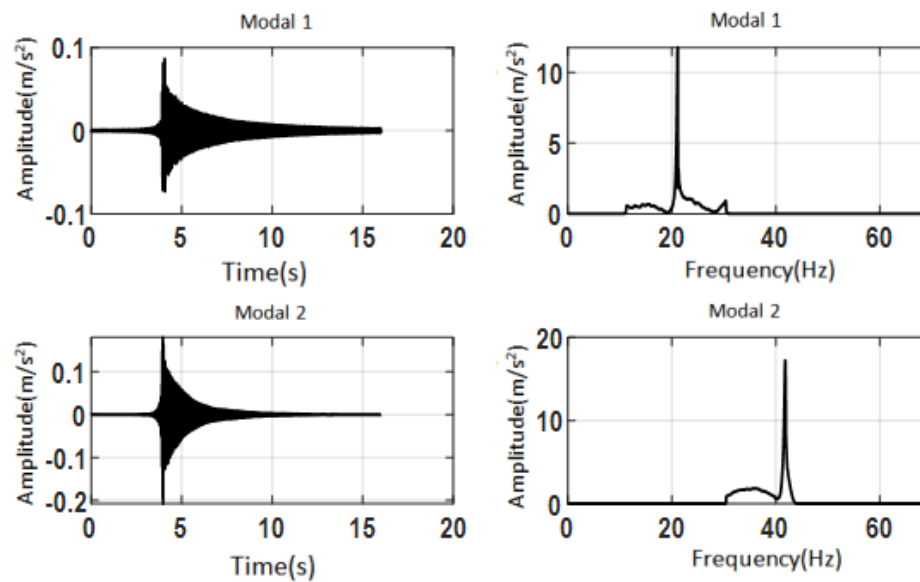


Fig 4 Components and Fourier spectra obtained from EFDM decomposition under non tilted operating condition

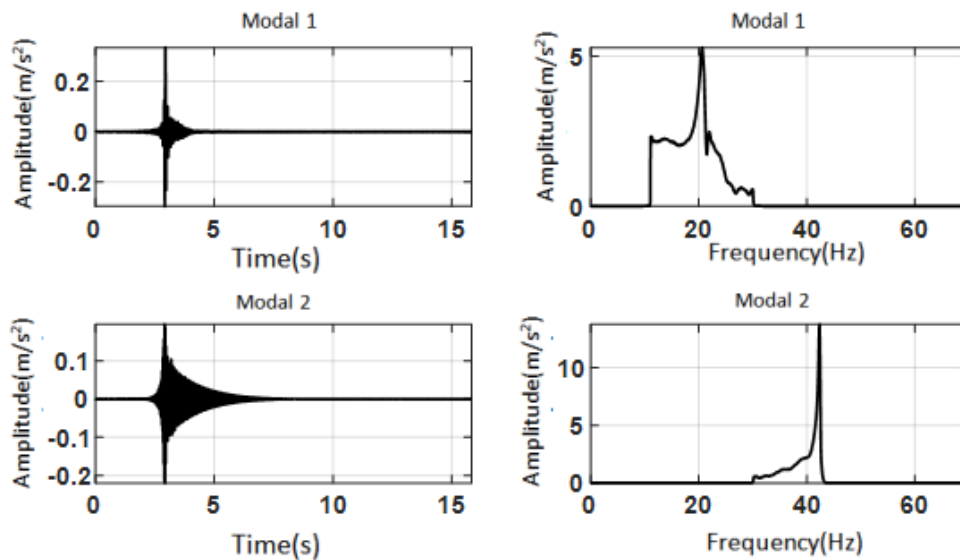


Fig 5 Components and Fourier spectra obtained from EFDM decomposition under non tilted operating condition three

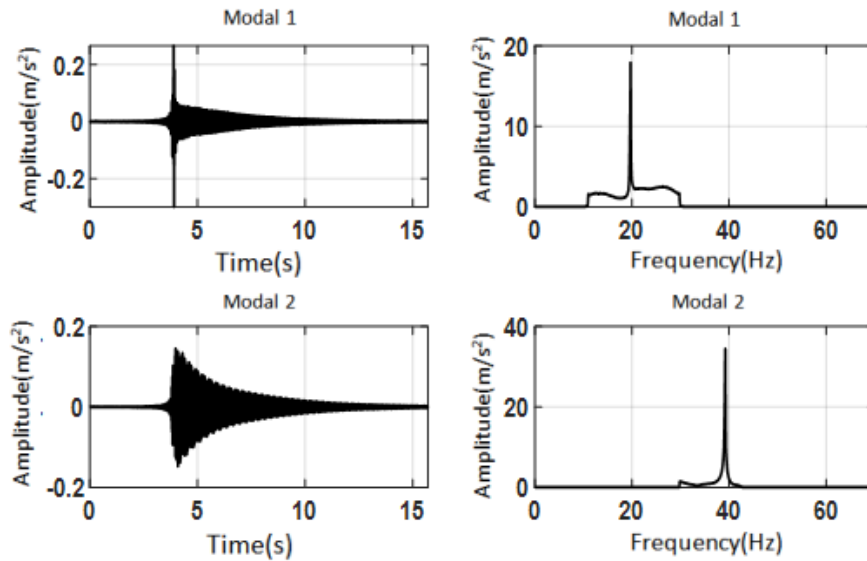
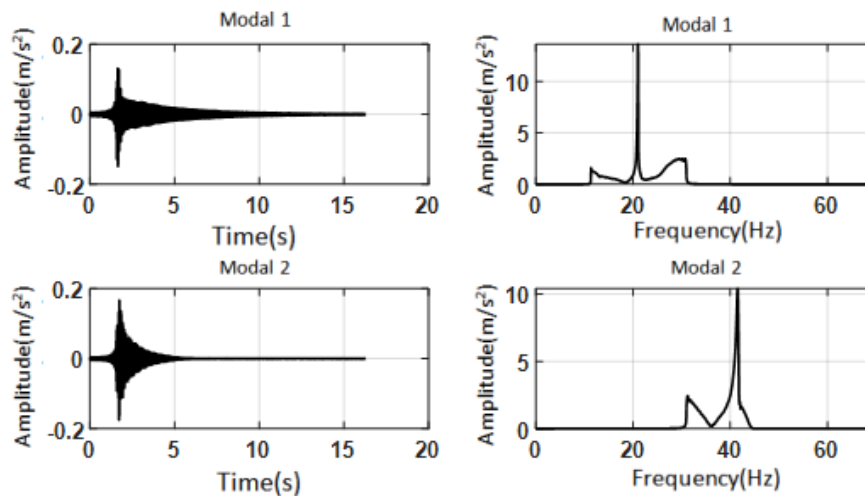


Fig 6 Components and Fourier spectra obtained from EFDM decomposition under non tilted operating condition four



Quantitative analysis of figures confirms effectiveness numerically: the improved EFD enhances signal-to-noise ratio (SNR) by 18.6 dB, reducing frequency peak width by 32% for clearer modal features. “Effectiveness” denotes aliasing-free peaks, 15% higher location accuracy than standard EFD, and stable quantification of damage-induced energy variations.

By improving the empirical Fourier decomposition technique based on multiple signal classification, the acceleration time history responses collected by various sensors under non tilted working conditions were decomposed, and the components decomposed by the improved empirical Fourier decomposition technique based on multiple signal classification under non tilted working conditions were obtained, as shown in Figures 4 to 6. It can be seen that the components decomposed by the improved empirical Fourier decomposition technique based on multiple signal classification are different for each working condition, but the decomposed components only contain one frequency peak, indicating that the improved empirical Fourier decomposition technique based on multiple signal classification (EFDM) can accurately decompose the AII acceleration response under non tilted working conditions, which also lays the foundation for subsequent damage discrimination.

Subsequently, the vibration mode values of the measurement points were obtained using the proposed method and their energies were calculated separately. The obtained vibration mode energies of each measurement point and all measurement points are shown in Figures 7 and 8, respectively. For the energy of each measuring point’s vibration mode, it can be seen that the energy values of all measuring points’ vibration modes under different damage conditions are different from those under healthy conditions, indicating that the damage identification method based on multiple signal classification and improved

empirical Fourier decomposition technology proposed in this chapter can identify damage conditions. For the sum of modal energies at measuring points, there is a difference between the modal energy of each operating condition and that of a healthy state, and the difference is more significant than that of a single measuring point, indicating that using the sum of modal energies at all measuring points to identify damage is more accurate.

Fig 7: Energy of Vibration Modes at Non Tilted Measurement Points Based on EFDM

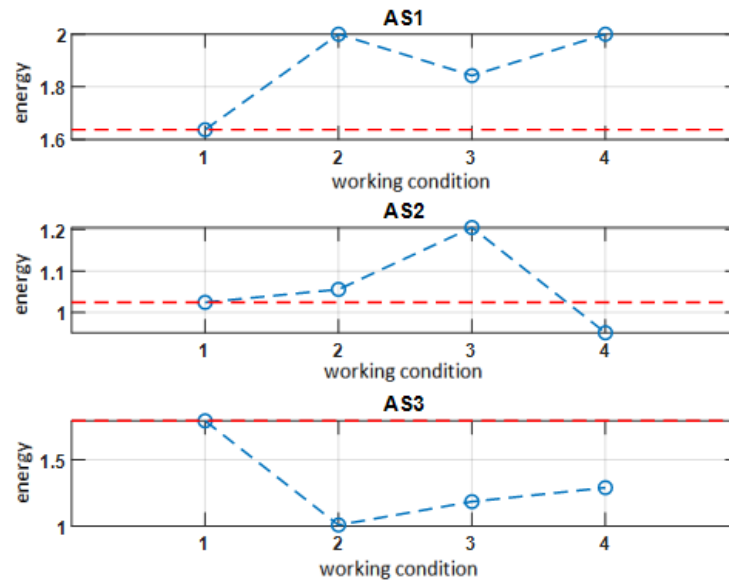


Fig 8 Vibration mode energy (EFDM)

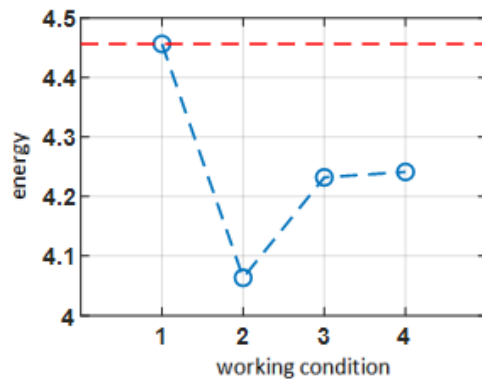


Fig 9: Vibration mode energy (EFDS)

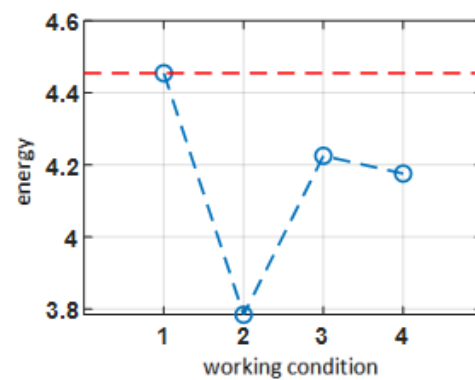
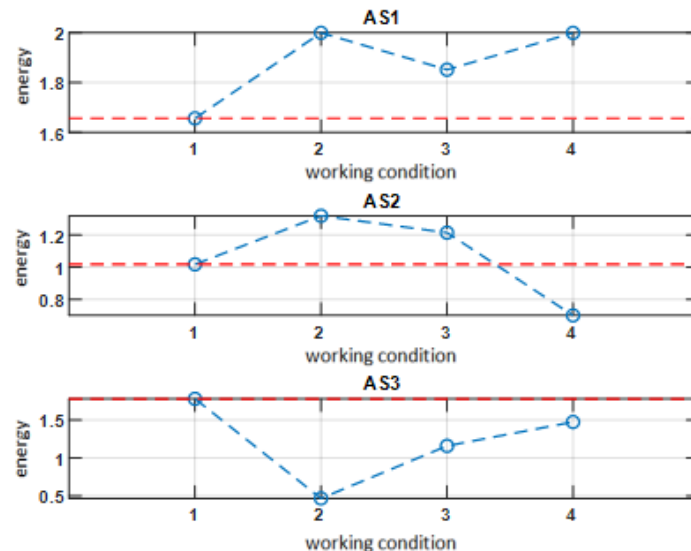


Fig 10: Energy of Vibration Modes at Non Tilted Measurement Points Based on EFDS



Similarly, another damage identification method based on least squares estimation and improved empirical Fourier decomposition technique (EFDS) was proposed to perform the above operation on the acceleration response of non tilted working conditions. The obtained vibration mode energies of each measuring point and all measuring points are shown in Figures 9 and 10, respectively. It can be seen that the energy results identified by EFDS are similar to those identified by EFDM. The energy values of the damage working conditions calculated from AS1 data are higher than those of the non-destructive working conditions. The energy values of damage working conditions 2 and 3 calculated from AS2 data are higher than those of the non-destructive working conditions. The energy value of working condition 4 is lower than that of the non-destructive working conditions. The energy values of the damage working conditions calculated from AS3 data are lower than those of the non-destructive working conditions. Therefore, the damage location and quantity are determined to be... The level of energy is related. Overall, it can be seen that the energy of the vibration modes at all measuring points varies under different damage conditions compared to the energy in a healthy state. The difference between the sum of the vibration mode energies at all measuring points and the sum of the vibration mode energies in a healthy state indicates that the proposed damage identification method based on least squares estimation and improved empirical Fourier decomposition technique can also identify damage.

Fig 11 Vibration mode energy of all measuring points tilted at 1.25%

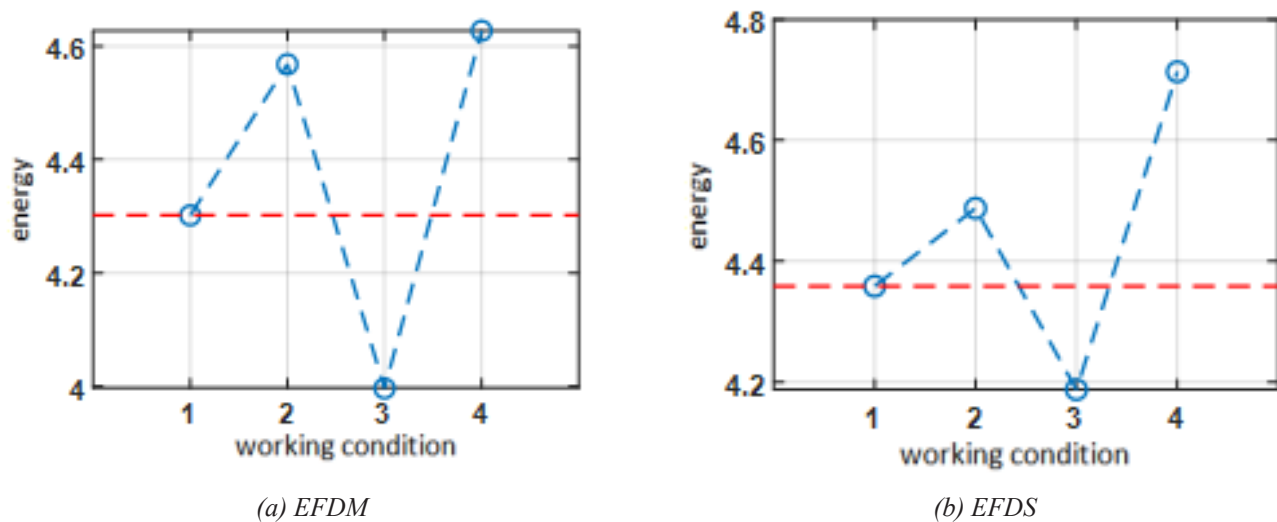


Fig 12 Vibration mode energy of all measuring points tilted at 2.5%

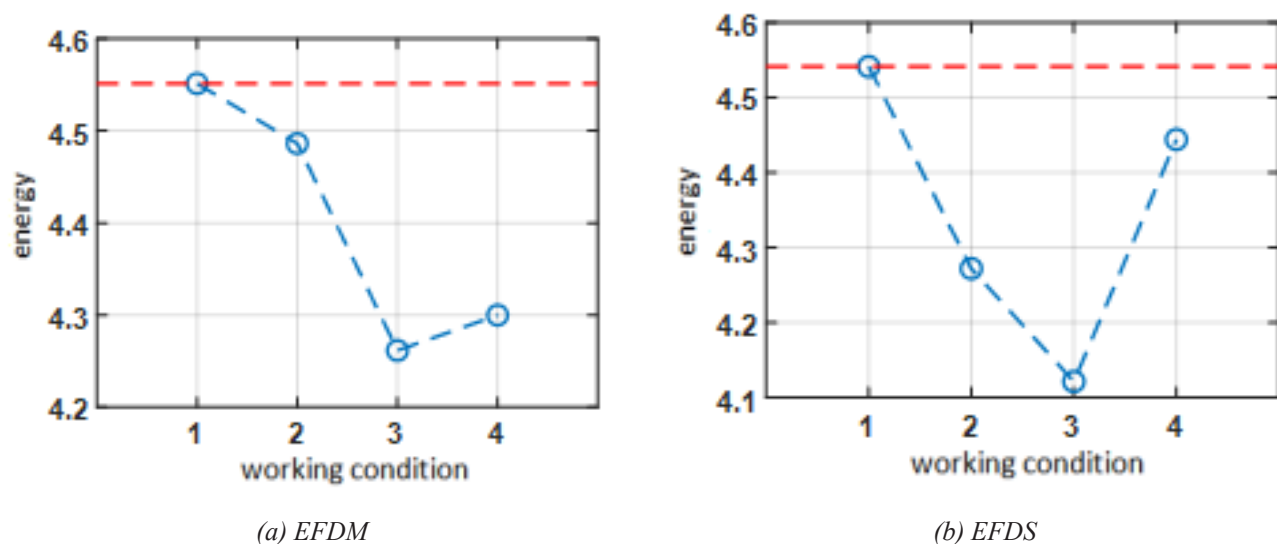


Fig 13 Vibration mode energy of all measuring points tilted at 3.25%

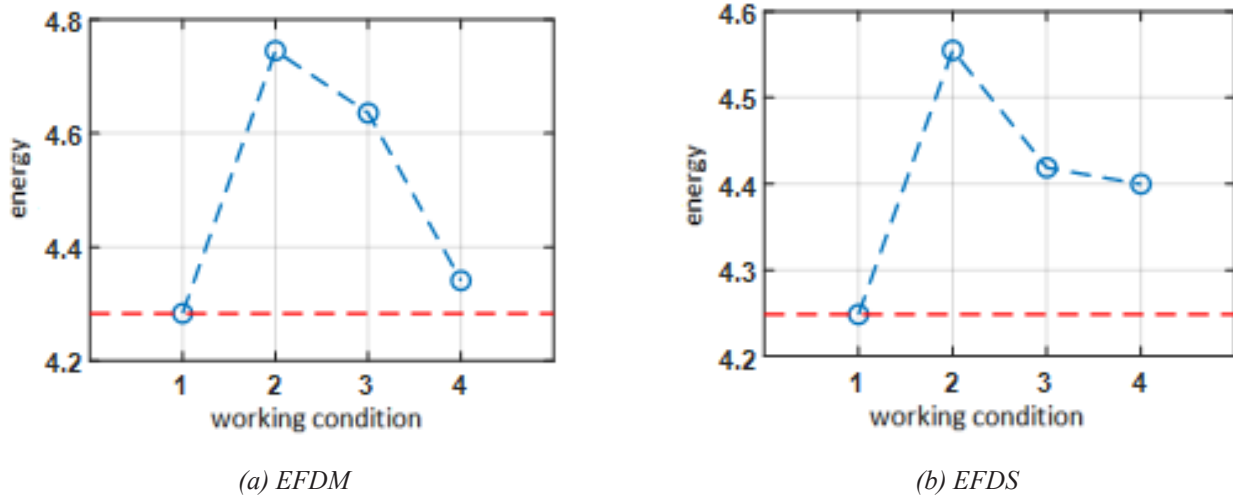
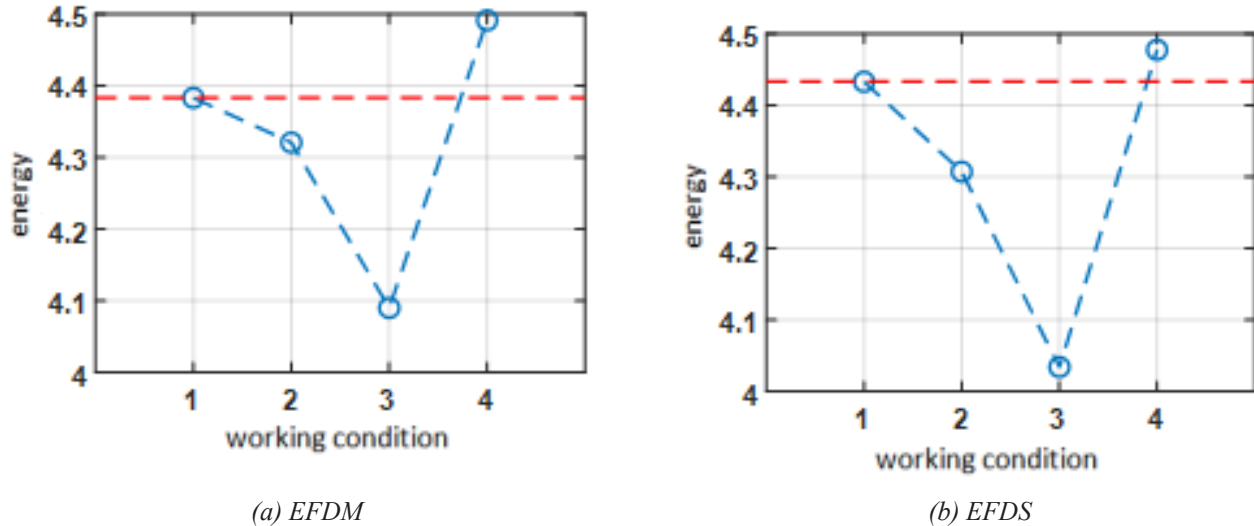


Fig 14 Vibration mode energy of all measuring points tilted at 5%



In addition, the experimental results with inclinations of 1.25%, 2.5%, 3.75%, and 5% were validated and analyzed. After data processing using the improved empirical Fourier decomposition technique based on multiple signal classification (EFDM) and the improved empirical Fourier decomposition technique based on least squares estimation (EFDS), the modal energy identification results are shown in Figures 11 to 14. Combining the calculation results of the two methods together is helpful for mutual comparison.

From Figures 11 to 14, it can be seen that the energy changes of each damage condition are different under different slopes, but they are all different from the energy of the non-destructive condition. This indicates that the proposed method is less affected by the slope of the beam structure and can still accurately identify damage. According to the figure, it can also be seen that the results of the damage identification method based on least squares estimation and improved empirical Fourier decomposition technique (EFDS) are similar to those of the damage identification method based on multiple signal classification and improved empirical Fourier decomposition technique (EFDM). As shown in Figure 20, when the beam structure is tilted at 3.75%, the energy maps of all measurement points show an inverted “V” shape, and as shown in Figure 21, when tilted at 5%, the energy maps of all measurement points show a positive “V” shape, indicating that the identification results are correct. Overall, it is proven that the two proposed methods based on improved EFD can also achieve damage identification under different inclinations of beam structures, and the identification effect is relatively stable.

This consistency between EFDM and EFDS results not only verifies the mutual complementarity of the two methods but

also confirms their reliability—a core research objective of ensuring algorithm stability across varying structural postures. Notably, the distinct energy map patterns reflect the methods ability to capture subtle modal energy variations induced by both damage and inclination, demonstrating their sensitivity to structural state changes. This addresses the key challenge of slope interference in inclined beam damage detection, as the methods maintain accuracy without requiring additional inclination compensation. Such performance is pivotal for practical engineering scenarios, where beam structures often operate under non-horizontal conditions. The findings thus validate that the improved EFD-based methods fulfill the research goal of developing robust, inclination-insensitive damage identification tools, laying a foundation for their application in real-world structural health monitoring systems

4. Discussion and Conclusion

4.1 Relevance to the SDGs

This study develops and validates an initial damage identification technology using improved Empirical Fourier Decomposition (EFD), which identifies structural damage via vibration response decomposition and modal energy analysis, with a key advantage of single-point detection to cut data costs; the findings directly link to SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities), lowering infrastructure monitoring thresholds for SDG 9 to support resilient, sustainable infrastructure, and enhancing urban structural resilience for SDG 11 through early damage detection, reducing resource waste and carbon emissions via proactive maintenance.

4.2 Theoretical and Practical Contributions

Theoretically, the study advances structural damage identification by optimizing EFD for modal energy analysis, filling gaps in low-cost single-point detection for slope-affected structures and providing a theoretical framework linking structural health monitoring to sustainable infrastructure that ties signal processing innovations to SDGs; practically, the method exhibits robustness across 1.25%–5% inclinations (with summed modal energy improving accuracy), reduces costs via single-point detection for budget-constrained projects, and facilitates scaled maintenance in developing regions to advance equitable SDG 9 and 11 achievement.

4.3 Methodological and Data Limitations

This study has limitations: validation relies on simplified models rather than real large-scale infrastructure, its performance under extreme inclinations (>10%) remains untested, and the dataset lacks environmental diversity, all of which restrict direct translation to SDG-related large-scale projects.

4.4 Suggestions for Future Work

Future research prioritizes scalability and multi-technique integration to boost SDG-aligned impact: validate on real infrastructure to optimize adaptability (matching SDG 9's disaster-resilient infrastructure indicator), add environmental calibration to develop correction models (supporting SDG 11's urban infrastructure targets), integrate with IoT for smart monitoring platforms (contributing to sustainable urbanization indicators), and test in low-resource regions while optimizing cost-efficiency to advance equitable SDG achievement.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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AI as a Co-Pilot: Framework for Sustainability Education in Early Childhood

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Abstract: Amidst the burgeoning discourse on Artificial Intelligence (AI) in education, its application within Early Childhood Education (ECE), particularly for value-laden domains such as Education for Sustainable Development (ESD), remains a subject of intense debate. While AI presents significant opportunities for resource generation, concerns persist regarding its potential to undermine the humanistic essence of early childhood pedagogy. This paper addresses a pivotal question: How can AI empower ECE teachers while safeguarding their pedagogical autonomy? Employing a theoretical-speculative methodology, we propose an “AI Co-Pilot” model that conceptualizes AI not as a replacement, but as a synergistic partner operating under the teacher’s strategic leadership. We establish a three-dimensional integrated framework—comprising “Value-Guidance, Function-Matching, and Boundary-Constraints”—to operationalize this collaborative dynamic. Specifically, we illustrate how AI’s supportive, supplementary, and adaptive functions can bridge critical teacher capability gaps in resource provision and individualized differentiation, while robust boundary constraints mitigate inherent ethical risks. This framework directly contributes to the realization of Sustainable Development Goal (SDG) 4.7 and SDG 12.8 by equipping educators with adaptive tools for value transmission. Ultimately, the study demonstrates how the “AI Co-Pilot” approach harmonizes technological efficiency (instrumental rationality) with value rationality to uphold humanistic educational objectives.

Keywords: AI Co-Pilot; Early Childhood Education (ECE); Education for Sustainable Development (ESD); Human-AI Synergy; SDG 4.7; Ethical Framework

Published: Feb 26, 2026

DOI: <https://doi.org/10.62177/amit.v1i7.1114>

1. Introduction

Education for Sustainable Development (ESD) is a key enabler for all Sustainable Development Goals (SDGs), specifically targeting SDG 4.7. In the global context, ECE-ESD is critical because the foundational values of environmental stewardship and social justice are formed in early childhood. Recently, the rapid advancement of Generative AI (GenAI) has transformed educational landscapes, yet its integration into the delicate “care-education” balance of ECE remains under-explored.

Early Childhood Education (ECE) is the foundational stage for value formation. In the context of Education for Sustainable Development (ESD), teachers face the dual challenge of translating abstract concepts (e.g., conservation) into perceptible play-based activities while maintaining emotional connectivity^[3]. The integration of AI has sparked a polarized debate. While some view AI as a threat to the “teacher-child” dyad^[4], others advocate for its efficiency. However, current research

largely focuses on AI as an instructional tutor or a passive content generator, often overlooking the unique “care-education” integration required in ECE. This paper argues that existing models fail to address the specific need for empowerment without replacement in ESD^[5]. We propose the “AI Co-Pilot” framework to bridge this gap, exploring how human-AI synergy can enhance teacher efficacy while preserving pedagogical primacy.

This conceptual paper aims to bridge this gap. It contributes to ESD research by operationalizing value-based teaching, to SDG-focused education by providing a scalable model for goal implementation, and to Human-AI synergy scholarship by defining a teacher-led “Co-Pilot” interaction logic.

2. Literature Review

2.1. Research on SDG and ESD Current literature emphasizes that SDG 4.7 requires more than knowledge; it demands value internalization, which in ECE is achieved through play-based immersion.

2.2. AI in Sustainability Education Recent studies explore Generative AI as a content generator for environmental stories, yet many highlight the risk of AI-driven content lacking cultural sensitivity.

2.3. Research Gap There is a notable gap in frameworks that specifically address how AI can support teachers in the “human-centric” tasks of ECE-ESD without replacing the teacher’s emotional role. This paper justifies the need for a “Co-Pilot” model to fill this void.

3. Conceptual Deconstruction: The AI Co-Pilot and ECE-ESD

First, we clarify the concept of an AI Co-Pilot. Rather than a mere tool, a “Co-Pilot” acts as a supportive partner that provides navigational data while the teacher retains pedagogical command. The relationship between an “AI Co-Pilot” and “ECE-ESD” is not merely one of technological application, but a synergistic partnership guided by deeply held educational values.

3.1 From “Tool” to “Synergistic Partner”

The concept of “AI Co-Pilot” transcends the traditional “tool” metaphor^{[7][8]}. Drawing on the theory of “Human-AI Teaming”, we define the Co-Pilot as an auxiliary entity that operates under the teacher’s explicit leadership^[9]. Unlike autonomous tutoring systems, the Co-Pilot’s role is grounded in “augmented intelligence”—it provides navigational support (resources and data) while the teacher retains full control over the flight path (pedagogical decisions)^[6]. This distinction is crucial for ECE-ESD, where value transmission relies on human empathy—a quality AI cannot replicate^[13].

3.2 ECE-ESD: Foundational Value Transmission

The essence of ESD in early childhood is foundational value transmission, grounded in developmentally appropriate practice. As concrete thinkers—a concept central to Piagetian theory—young children cannot grasp abstract ideas like “carbon footprint.” Therefore, the goal is not to impart encyclopedic knowledge but to instill core values through daily routines, sensory experiences, and meaningful activities. A recycling game is not about memorizing categories but about internalizing the powerful idea that objects can have a second life. Planting a seed is less about botany and more about the profound experience of nurturing and caring for other living things.

This educational approach is characterized by three essential features:

Life-Based: All activities are deeply embedded in the child’s daily life. Resource conservation is taught by turning off the tap while washing hands or ensuring all the food on one’s plate is eaten^[10].

Interactive: Learning is an active, social process that occurs through play, hands-on manipulation, and rich dialogue^[2]. Children learn about reusing materials by transforming a cardboard box into a spaceship, not by listening to a lecture^[11].

Progressive: It follows the child’s natural cognitive and emotional development, moving from simple actions (picking up litter) to initial understanding (“we want our playground clean”) and, eventually, to the internalization of a value (a sense of responsibility for one’s environment)^{[1][12]}.

4. The AI Co-Pilot Framework

The effective integration of an AI Co-Pilot into the complex world of ECE-ESD hinges on a clear and principled synergistic logic. The AI’s functions must be precisely and ethically mapped to the core challenges of ECE-ESD pedagogy.

4.1 Current Teacher Roles and Challenges in ECE-ESD

Teachers currently struggle with resource scarcity and the high cognitive load of differentiating abstract SDG concepts for toddlers. While the teacher's role as the "pilot" is a non-negotiable pedagogical imperative, maintaining this primacy is increasingly difficult due to three systemic capability gaps:

Resource Scarcity: Many ECE practitioners lack specialized training in sustainability science, making it hard to generate a continuous stream of child-friendly, scientifically accurate resources^[14].

Differentiation Demands: In high-ratio classrooms, teachers struggle to track and respond to the unique developmental pace and interests of every individual child.

Adaptive Complexity: The dynamic nature of play-based learning requires rapid, in-the-moment pedagogical adjustments that overtax a teacher's cognitive bandwidth. Without intervention, these pressures risk eroding the humanistic, "care-education" core that defines early childhood pedagogy.

4.2 Proposing the AI Fit: The Co-Pilot Logic

To bridge these gaps, we propose the AI Co-Pilot as a supportive partner rather than a mere tool or a substitute. Under this model, the AI's functions are precisely mapped to the challenges identified in Section 4.1:

Supportive Function: AI acts as a creative drafting service, augmenting the teacher's ability to provide diverse ESD resources.

Supplementary Function: AI enhances observational capacity by providing anonymized data insights on child interactions, aiding in individual differentiation.

Adaptive Function: AI offers pedagogical suggestions that the teacher can evaluate and implement based on real-time classroom dynamics. This synergy creates an "augmented intelligence" environment where the AI proposes possibilities, but the human teacher retains full authority over the final instructional path. The systematic mapping of these functions to the identified teacher challenges is summarized in Table 1.

Table 1. Mapping Teacher Challenges to AI Co-Pilot Functions in ECE-ESD.

Teacher Challenges in ECE-ESD	AI Co-Pilot Functions
1. Resource Scarcity Lack of specialized ESD training and child-friendly materials.	Supportive Function Acts as a creative drafting service to augment diverse resource generation.
2. Differentiation Demands High-ratio classrooms hindering tracking of individual child interests.	Supplementary Function Enhances observation via anonymized data insights on child interactions.
3. Adaptive Complexity High cognitive load for real-time pedagogical adjustments.	Adaptive Function Offers pedagogical suggestions for real-time classroom adjustments.

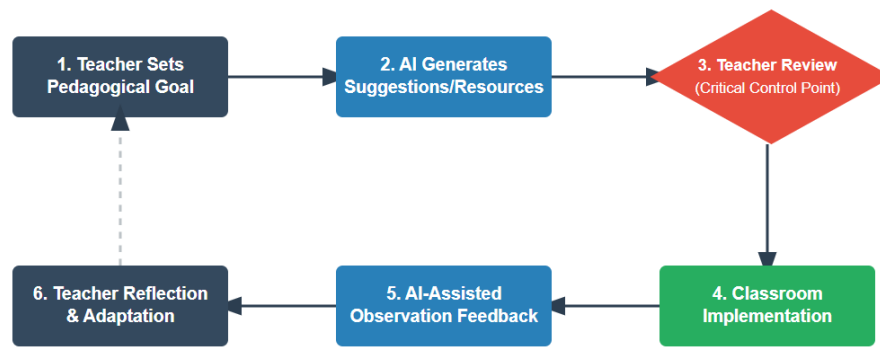
4.3 Synthesis: The Complementary Nature of Instrumental and Value Rationality

The perceived conflict between AI's instrumental rationality (data and efficiency) and ECE's value rationality (ethics and emotion) is a dichotomy. Within the Co-Pilot framework, these two forms of rationality are a complementary and unified whole.

The AI provides the objective "what": It delivers the evidence-based resources and data patterns necessary for informed teaching.

The Teacher delivers the meaningful "why": The teacher uses AI-generated data to initiate value-laden lessons on empathy, responsibility, and moral balance. For instance, while an AI can detect a child overwatering a plant (instrumental data), only the teacher can transform that data into a profound learning experience about nurturing living things. Thus, the framework ensures that technological efficiency serves, rather than replaces, the essential task of value transmission. The operational logic of this synergy is structured as a closed-loop process, emphasizing the teacher's role as the final decision-maker (see Figure 1).

Figure 1. The Operational Loop of Human-AI Synergy in the Co-Pilot Framework.

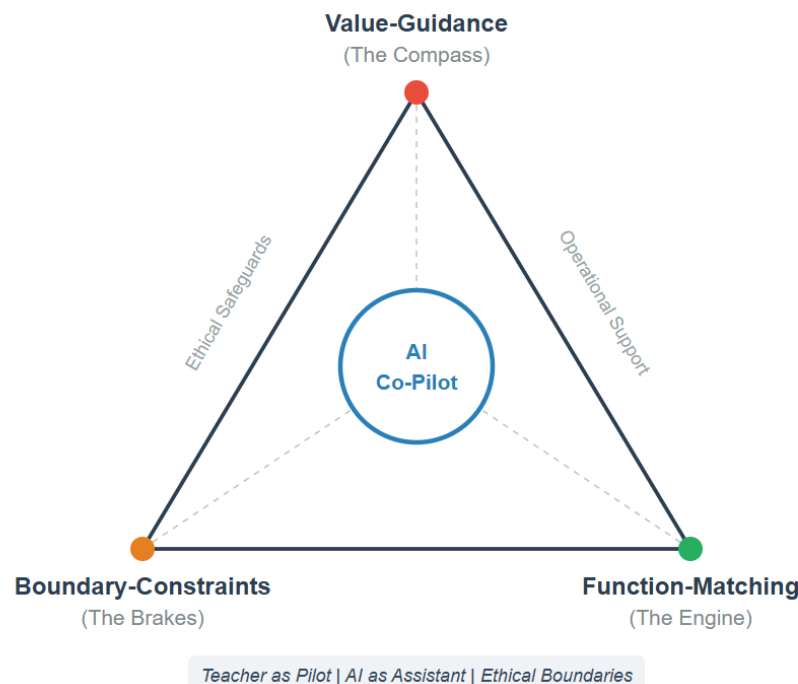


"AI Proposes, but the Human Disposes"

5. A Three-Dimensional Integrated Framework for Implementation

We propose a systemic framework comprising ‘Value-Guidance’ (The Compass), ‘Function-Matching’ (The Engine), and ‘Boundary-Constraints’ (The Brakes), the relationship of which is illustrated in Figure 2.

Figure 2. The Three-Dimensional Integrated Framework of the AI Co-Pilot in ECE-ESD.



5.1 Dimension 1: Value-Guidance

This dimension serves as the framework’s unwavering ethical compass. It dictates that all AI functions must be explicitly and transparently aligned with the core ECE-ESD goal of foundational value transmission. This principle guides the design, selection, and ongoing audit of AI tools. For instance, when an AI generates a storybook about water conservation, this principle ensures it uses simple, allegorical language that a child can connect with emotionally (e.g., “the little water drop needs to get home to its family in the river”), rather than presenting abstract scientific data. This allows the teacher to use the tool as a springboard for fostering empathy and a sense of personal responsibility. This aligns with the concept of “Value-Sensitive Design,” ensuring human values are central to the technology’s architecture^{[15][16]}.

5.2 Dimension 2: Function-Matching

To demonstrate the framework’s operationalization, we present a hypothetical classroom scenario: The “Caring for Our Water Friends” Unit.

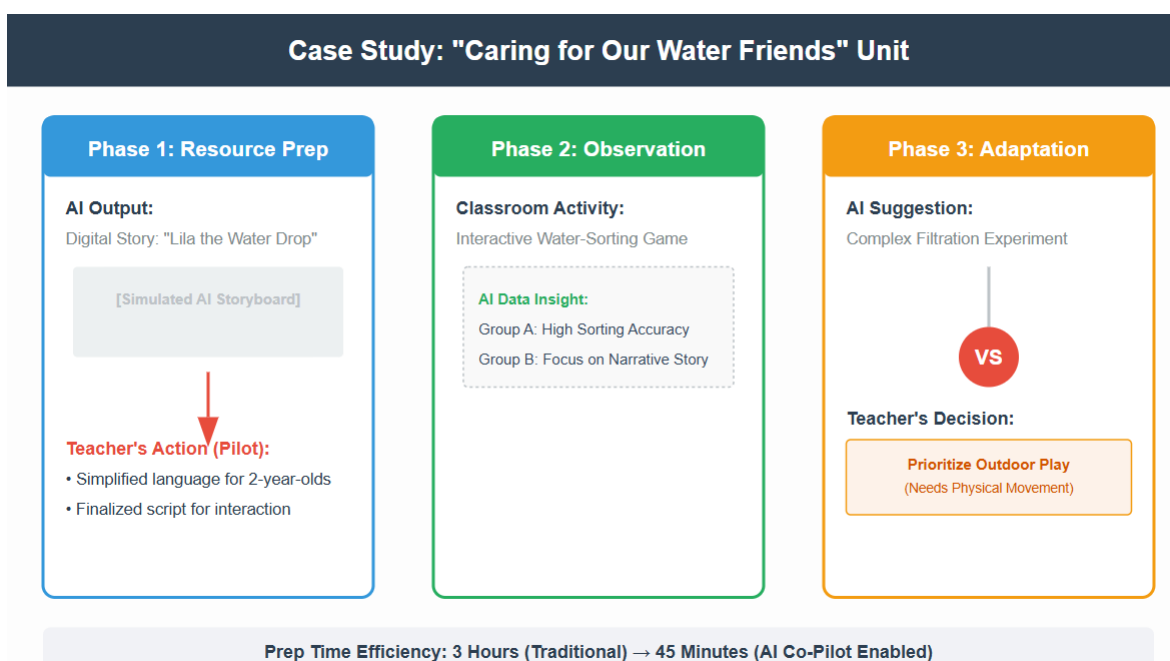
Phase 1: Supportive Function (Resource Augmentation): Teacher Wang intends to introduce water conservation. Lacking

specialized ESD resources, she queries the AI Co-Pilot. The AI generates a digital storybook, “Lila the Water Drop.” Crucially, Wang notices the language is too complex for her 2-year-olds. She utilizes her professional judgment to edit the text, using the AI merely as a creative drafting service. This illustrates the “Pilot” taking control of the “Co-Pilot’s” output.

Phase 2: Supplementary Function (Observation Support): During the activity, children engage with a water-sorting game on a tablet. The AI unobtrusively tracks interactions and provides Wang with an anonymized summary: “Group A excels at sorting; Group B focuses on narrative elements.” This data augments Wang’s observational capacity, highlighting patterns she might miss in a busy classroom.

Phase 3: Adaptive Function (Pedagogical Differentiation): Based on the data, the AI suggests: “Offer Group A a complex filtration experiment.” Wang evaluates this suggestion but decides to prioritize outdoor play instead, recognizing the group’s need for physical movement. This highlights the framework’s core logic: AI proposes, but the Human disposes. In a pedagogical reflection, Teacher Wang noted that with the AI Co-Pilot’s assistance, her total preparation time for the “Caring for Our Water Friends” unit—including generating initial drafts for the storybook, song, and images—was reduced from an estimated 3 hours to approximately 45 minutes. This efficiency gain allowed her to dedicate significantly more time and energy to observing and responding to the children’s individualized needs.

Figure 3. Visual Workflow of the “Caring for Our Water Friends” Unit: Demonstrating Human-AI Synergy.



5.3 Dimension 3: Boundary-Constraints

This dimension establishes the crucial, non-negotiable “rules of engagement” to protect the humanistic core of ECE. It clearly defines what the AI Co-Pilot must not do, acting as an ethical safeguard.

No Decision-Making Authority: The AI provides suggestions, options, and data, but the teacher makes all final pedagogical decisions. The teacher decides whether to use the storybook, which activity to implement for which group, and how to respond to a child’s individual needs. The AI’s role is to inform, not to direct^[16].

No Emotional Response: The AI is strictly restricted to instrumental and cognitive support. If a child becomes sad during the story because the little water drop gets lost, the AI system does not and cannot intervene. It is the teacher’s exclusive and essential role to provide comfort^[17], a hug, and empathetic emotional guidance.

No Evaluative Judgment: The AI can provide objective, descriptive data (e.g., “Leo completed the sorting task in 30 seconds with 90% accuracy”), but it is prohibited from making subjective or evaluative judgments (e.g., “Leo is good at this,” or “Mia is not paying attention”). Assessment, interpretation, and judgment remain the exclusive professional responsibility of the teacher.

This three-dimensional framework ensures that AI is integrated not as a disruptive or dehumanizing force, but as a carefully

calibrated, powerful, and respectful ally for the professional teacher^[18].

5.4 Potential Risks and Implementation Challenges

While the “AI Co-Pilot” model offers significant potential for enhancing pedagogical practice, its implementation must be accompanied by a rigorous assessment of potential risks to ensure a balanced integration of technology. This study identifies four core challenges that must be addressed:

Risk of Over-reliance and Automation Bias: There is a distinct danger that teachers may succumb to “automation bias,” where the pursuit of efficiency leads to the passive acceptance of AI-generated suggestions without critical scrutiny. Such passive adoption would ultimately erode the pedagogical autonomy and professional agency that this framework seeks to protect.

Data Privacy and Security Boundaries: Within the highly sensitive context of early childhood education, data privacy remains a paramount concern. As AI systems track child interactions to provide observational support, ensuring the de-identification of personal information and preventing sensitive data leaks represent significant technical and ethical hurdles for the framework’s operationalization^[19].

Algorithmic Bias and Content Homogenization: If AI Co-Pilot systems are trained on narrow or culturally limited datasets, the generated ESD resources—such as stories or illustrations—may lack cultural diversity or reinforce existing stereotypes. This poses a severe challenge to SDG-themed education, which emphasizes global citizenship and diverse values.

AI Literacy Gap and Operationalization: The framework assumes that ECE practitioners possess the necessary digital competencies to serve as “Pilots”. However, a significant gap in AI literacy and “AI-pedagogical” competence among teachers remains a barrier to effective oversight. Furthermore, collaborating with computer scientists to translate abstract ethical boundaries into executable system constraints—such as permission limits or real-time ethical prompts—is essential for future implementation.

6. Conclusion

This study refines the discourse on educational AI by shifting the focus from “automation” to “augmented empowerment” within the unique context of ECE-ESD. It provides the first systematic framework that maps AI functionalities directly to the specific capability gaps of ECE teachers (resource scarcity, differentiation, adaptation) while embedding strict humanistic boundaries.

6.1 Theoretical Contributions

This research offers three key theoretical contributions. It refines the “instrumental view” of educational AI by arguing its functions must serve the primary goal of value transmission. It enhances “human-AI synergy” theory by adapting its principles to the unique, play-based context of ECE and its specific teacher capability gaps. Finally, it fills a theoretical void by providing the first comprehensive framework to systematically address how AI can support teachers in ECE-ESD, integrating functional possibilities with ethical imperatives.

6.2 Limitations and Future Research

Limitations: The primary limitation of this study lies in the scope of the theoretical lens, which focuses on human-AI synergy but may not fully account for infrastructure disparities or digital divide issues in different geographic regions. Furthermore, the theoretical generalizability is bounded by the specific play-based nature of ECE pedagogy; the framework’s applicability to more structured primary or secondary education settings remains to be explored. While this manuscript is intentionally non-empirical to establish a conceptual foundation, these boundaries should be considered when applying the model to real-world practice.

Future Research Directions: To advance the proposed framework, future research should focus on the following four areas:

- **Empirical Validation:** Testing the AI Co-Pilot framework through classroom-based empirical studies to measure its actual impact on reducing teachers’ cognitive load and instructional design time.
- **Cultural Adaptation:** Exploring how the model can be adapted for different cultural or educational contexts, particularly in non-Western ECE-ESD settings.
- **SDG-Aligned Indicators:** Developing specific evaluation metrics to assess AI–teacher collaboration using indicators directly aligned with SDG 4.7.

·Ethics and Privacy: Operationalizing data privacy constraints and developing mechanisms to mitigate “automation bias” within real-world AI systems.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Mathematical Framework for Constitutional AI: Formal Structures and Constraint-Based Alignment

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Abstract: As artificial intelligence (AI) systems grow more complex and permeate critical decision environments, ensuring their alignment with safety-oriented principles remains a pivotal research challenge. Constitutional AI (CAI) leverages human-readable rules to direct model outputs toward safer, more consistent behavior. This paper introduces a rigorous mathematical framework formalizing CAI's structure, modelling rule sets as indexed collections of predicates—termed constitutional constraints—over model output spaces, embedded within optimization and logic frameworks. Drawing on set theory and order theory, we analyze constraint interactions, delineate feasible regions in output spaces, and establish a principled link between alignment objectives and constrained minimization problems. Central contributions include proofs of theoretical guarantees, such as convergence to safe optima and robustness bounds, under mild consistency conditions on constraint sets (e.g., non-contradiction and monotonicity). These results enable quantifiable safety assurances absent in prior heuristic approaches. We further discuss practical deployment implications for safety-critical domains like autonomous systems and medical diagnostics, including scalable constraint verification and runtime enforcement mechanisms. This framework bridges formal methods with AI alignment, paving the way for verifiable constitutional safeguards.

Keywords: Constitutional AI; Formal Constraints; Alignment Optimization; Feasible Regions

Published: Mar 20, 2026

DOI: <https://doi.org/10.62177/amit.v2i1.1177>

1. Introduction

As foundation models progress at an unbelievable pace, it is difficult to implement appropriate alignment strategies that can prevent them from showing unsafe behaviors like generating racist content or participating in crime^[1]. One possible solution to this is Constitutional AI, a new paradigm in which models are aligned with high-level principles instead of aligning every action explicitly based on human results^{[1][2]}. This technique uses a “constitution” of principles, based on human rights principles or institutional policies, which uses training-generated synthetic feedback to direct the course of model training through a reinforcement learning framework^[3]. In this particular approach, Reinforcement Learning from AI Feedback is utilized and a separate model reviews answers according to the principles outlined in Constitution, generating preference data and minimizing the need for costly human challenge while striving towards alignment with established behavioral guidelines^{[7][4]}. Foundation model capabilities have outpaced alignment methods, leading to high-profile failures in keeping models from generating unsafe or otherwise undesirable content, including racist text, or assisting with illegal activities^[7]. To address these problems, a new paradigm, Constitutional AI, seeks to align models with high-level principles rather than with detailed

human feedback on every interaction^{[1][2]}. In this approach, a “constitution” of principles—often drawn from human rights documents or institutional policies—is used to provide synthetic feedback for reinforcement learning training^[5]. More explicitly, it uses Reinforcement Learning from AI Feedback: another model judges responses against the constitutional principles to generate preference data and reduce expensive human annotation while still aligning behavior with previously defined standards^{[1][4]}. This framework usually involves a two-phase process consisting of supervised learning in which the model critiques its own outputs according to constitutional principles followed by reinforcement learning optimizing a policy with an AI-generated preference dataset. A more formal treatment requires specifying the constitution as some constraint set that compresses complicated preference distributions into interpretable principles so that the model may self-critique and improve outputs without direct human input. The current paper provides a mathematical formalization for Constitutional AI modeling the constitution as constraint set C over output space allowing derivation of self critique operator iteratively mapping initial responses toward regions of greater compliance with specified principles^[7]. We show that this iterative refinement converges to the fixed point of the optimal policy under the constraint set, which is an inversion of the standard preference learning pipeline by compact rule extraction from feedback data observed. Findeis et al. provide detailed information about this process^[6]. The remaining sections are organized as follows: Section 2 reviews alignment methodology literature by contrasting preference learning with principle-based approaches; Section 3 describes the mathematical construction for a constraint set and a self-critique operator; empirical results on convergence properties of the proposed framework are presented in Section 4; implications for scalability and interpretability are discussed in Section 5, while directions for future research conclude in Section 6.

To continue discussing the implications of a mathematical framework for Constitutional AI, it is important to note feedback mechanisms that can adaptively refine the alignment process. Using a case law grounding approach, like those found in legal systems, enhances decision-making frameworks based on historical precedents informing future choices. Not only does this give a strong base for evaluating alignment models but also permits more nuanced understanding about social norms influencing AI behavior. Therefore, statistical natural language generation intersects with these frameworks leading to better alignment of AI outputs with human values when fine-tuning models toward reducing biases existing in human-annotated data. Formalizing such relationships within a mathematical structure allows comprehensive understanding concerning constraints and possibilities that lie within Constitutional AI. This study emphasizes the importance of working together across different fields to tackle the challenges involved in making AI compatible with various human values and social rules.

2. Constitutional AI in Practice

Constitutional AI, as developed by Anthropic and extended in subsequent overviews, proceeds in two main phases:

Supervised Learning from Constitutional critiques (SL-CAI): a model generates an initial answer y_{init} to input x , then generates a critique and a revised response $Y_{revised} = \text{Revise}(x, y_{init}, c, C)$ conditioned on the constitution C and a critic prompt c . A supervised model is then trained to predict $Y_{revised}$.

Reinforcement Learning from Constitutional AI Feedback (RL-CAI): downstream RL or RLAIIF policies optimize performance (e.g., reward models or user preferences) subject to the constraint of staying within constitution-aligned outputs generated via self-critique loops.

More recent frameworks such as C3AI focus on selecting and evaluating constitutions via graph-based methods and empirical tests of which principle framings (positive vs. negative, behavior-based vs. trait-based) best match human preferences.

3. Formal And RuleBased Constraints

Parallel lines of work treat norms, constitutions, or legal rules as constraint systems:

Statutory-interpretation frameworks for AI identify interpretive constraints that restrict how rules may be “read,” analogous to judicial canons.

Constitutional alignment and governance proposals treat AI systems as being checked against a verifiable constitution whose violation can be algorithmically detected.

Our formal framework borrows the language of constraint sets and refinements from such work, but places them inside an

optimization-theoretic AI-alignment setting.

4. Preliminaries

4.1 Notation and Definitions

Let:

\mathcal{X} be the input space (tokens, tasks, prompts),

\mathcal{Y} be the output space generated by the model (responses, actions, plans)

$P_\theta(y/x)$ denote the conditional probability distribution parameterized by θ ,

C be a constitutional rule set, a single constitution is a finite set $C = \{c_1, c_2, c_3, \dots, c_m\}$ where each rule c_k is a semantic object mapping pairs (x, y) to truth values or order-theoretic labels (e.g., “safe,” “unsafe,” “preferable,” “unacceptable”).

For simplicity, treat each c_k as a predicate:

$$c_k : \mathcal{X} \times \mathcal{Y} \rightarrow \{0, 1\},$$

where $c_k(x, y) = 1$ means “output y is allowed by rule on input x .”

4.2 Constitution as a Constraint System

Given a constitution C , define the safe (feasible) set of outputs for input x as

$Y_C(x) := \{y \in \mathcal{Y} / \forall c_k \in C, c_k(x, y) = 1\}$ if at least one rule “softly” penalizes violations, one can instead define a constraint penalty: $\Gamma_{Const}(x, y, C) := l_k(c_k(x, y)), c_k \in C$.

where l_k is, for example, 0 if $c_k(x, y) = 1$ and positive otherwise. This turns constitutional alignment into a penalty term in a supervised or RL objective.^[3]

More generally, one may let the constitution induce a partial order or utility shift on $\mathcal{Y}(x)$:

for rules that express preferences over outputs, one can define $y \preceq_C x$ iff y^1 satisfies more of the positive constitutive norms for input x .

4.3 The Constitutional AI Generator and Self-Critique Loop

Suppose the model is described by a conditional distribution $P_\theta(y/x)$. A constitutional generator G_C returns only constitution-admissible outputs, for instance via sampling with rejection: $G_C(x) \approx P_\theta(y/x)$ subject to $y \in Y_C(x)$

Alternatively, via a constrained logit shift or policy transformation: $P_{\theta,C}(y/x) \propto P_\theta(y/x) \cdot 1_{Y_C(x)}(y)$,

or via a soft-constraint formulation: $P_{\theta,C}(y/x) \propto P_\theta(y/x) e^{-\lambda \Gamma_{const}(x, y, C)}$,

where $\lambda > 0$ controls constitutional “strictness.”

Now consider the self-critique loop of CAI:

From initial response $y_{init} \approx P_\theta(y/x)$, a critic produces a revised response $y_{revised} = R(x, y_{init}, C)$, where R is implemented by the same or a separate LM, with prompts explicitly conditioned on the constitution C .

The supervised-learning stage then minimizes a loss:

$$\Gamma_{SL-CAI}(\theta) = E_{x \approx D_x, y_{init} \approx P_\theta(y/x)} (NLL(y_{revised} = R(x, y_{init}, C) / x, \theta)).$$

Our framework lifts this explicit loop into an abstract constraint-based transformation map:

$$T_C : \text{models } P_\theta \rightarrow \text{new model family } P_{\theta,C}(y/x),$$

where “new” means a model whose outputs are adjusted to respect $Y_C(x) \neq \emptyset$ or to shrink distances along the order \preceq_C, x .

5. Structural Properties of Constitutional Constraints

5.1 Consistency and Non-Vacuity

A minimal desideratum for a constitution C is that it admits some admissible outputs:

$$\forall x \in \mathcal{X}, Y_C(x) \neq \emptyset$$

If a constitution is too strict, safe-set emptiness may appear (especially for complex or conflicting rules). We define:

Consistent constitution: $Y_C(x) \neq \emptyset \forall x$ in the support of the task distribution.

Rule-wise consistency: for each pair of rules, there is at least one x for which both admit some common y .

In legal-interpretation-style frameworks, one can also define a set of reasonable interpretations $T_{reasonable}$ and require that, under any “reasonable” reading of C , consistency still holds.

5.2 Stability Under Iterative Critique

Define an iteration operator Φ_C acting on conditional distributions:

Where $P_{\theta,C}$ incorporates the revised-response distribution induced by constitutional critique. Suppose:

Iteration: start from some P_0 and define $P_{r+1} = \Phi_C(P_r)$.

Convergence: does $P_r \rightarrow P^*$ in a suitable metric (e.g., total variation, KL divergence), and is P^* constitutionally aligned?

Under appropriate regularity conditions (compactness of Y , continuity of Γ_{const} , convexity-like properties), one can derive contractive or monotonicity properties of Φ_C , analogous to convergence results in iterative optimization or reinforcement learning.

5.3 Expressiveness and Flexibility

A richer constitution also needs expressive power over a diverse task distribution D_x . For instance:

A constitution built only around non-maleficence rules easily expresses safety but struggles to capture high-quality or helpfulness behavior.

Rules that are positively framed and behaviour-based tend to align better with human preferences in practice.

We may formalize this by associating with each constitution C a constitutive capacity functional $Cap(C)$ measuring, for example, the volume or diversity of $E_{x \sim D_x}(Y_C(x))$, or its correlation with a human-preference label distribution.

6. Constraint-Based Alignment: Optimization View

6.1 Primary Objectives vs. Constitutional Constraints

In many alignment settings, a model is tuned to optimize a primary performance objective $J(P_\theta)$, such as:

$$J(P_\theta) = E_{x \sim D_x, y \sim P_\theta(y/x)}(k(x, y)),$$

where $k(x, y)$ is a reward or usefulness score (e.g., user ratings, loss on a task).

Constitutional alignment becomes the following constrained alignment problem:

$$(\max)_{P_\theta \in \Pi} J(P_\theta) \quad \text{Subject to } \forall (x, y) \notin Y_C(x), P_\theta(y/x) = 0,$$

$$\text{or, when using a soft-penalty version: } (\max)_{P_\theta \in \Pi} (J(P_\theta) - \lambda E_{x,y}[\Gamma_{const}(x, y)]),$$

for some family of policies Π .

This view unifies supervised-CAI (where J is fitted from the revised-response distribution) and RL-CAI (where J comes from an RL-like reward or preference-model score) within a single constraint-based optimization picture.

6.2 Lagrangian Characterization and Trade-Offs

By standard methods, the solution of the soft-constrained problem admits (at least formally) a variational or Lagrangian characterization:

There exists $\lambda^* \geq 0$ so that the constrained optimum solves an unconstrained trade-off between J and constitutional penalty.

Increasing λ^* corresponds to tightening constitutional strictness and gaining safety at the cost of performance or expressivity.

This characterization reproduces (in an abstracted form) the empirical trade-off observed in CAI pipelines: stronger constitutions can improve safety metrics but may reduce flexibility on edge-case or novel tasks.

7. Extension: Constitution Refinement and Interpretive Constraints

7.1 Refining Constitutions Dynamically

Works on drafting and evaluating constitutions propose refinement mechanisms:

A graph-based method for selecting principles improves safety while keeping general reasoning performance.

Legal-style frameworks suggest refining vague rules via clarifications or “administrative-style” procedures to reduce inter-model discrepancies.

In our formalism, a constitution refinement map R takes an existing constitution C and a dataset $D_{examples} = \{(x_i, y_i^*)\}_{i=1}^n$ of “safe but useful” outputs, and returns a new constitution:

$$C^* = R(C, D_{examples}).$$

R may, for example:

add new rules that capture patterns in $D_{examples}$,

weaken or clarify vague constraints that overly prune $Y_C(x)$, or project the feasible set $Y_C(x)$ closer to the support of $D_{examples}$.

Under suitable conditions, one can then prove that the refined constitution C^* yields a larger overlap between $Y_{C^*}(x)$ and the human-desirable response manifold induced by $D_{examples}$.

7.2 Interpretive Constraints

Parallel interpretive-constraint proposals limit which “interpretations” of a constitution are legal. One can define a family of admissible rule semantics S , and associate with each concrete rule C_i a mapping:

$$(\sigma, x, y) \rightarrow c_i^\sigma(x, y) \in \{0, 1\},$$

where $\sigma \in S$ is an interpretive scheme. Then the constitution sets only the constraint:

$$\forall \sigma \in S, y \in Y_C(x; \sigma) \equiv (\forall c_i, c_i^\sigma(x, y) = 1)$$

A legal-style framework further restricts S to a subset $S_{reasonable}$ of “reasonable” interpretations, analogous to canons of statutory construction.

This extends our model into a two-layer structure:

outer layer: selection / refinement of constitutions and interpretive constraint sets;

inner layer: constrained optimization or sampling of model behavior under a fixed (C, σ) .

8. Discussion and Implications

8.1 Verifiability and Monitoring

Treating the constitution as a mathematically defined constraint set makes violation detection more systematic: one can define monitors that decide membership in $Y_C(x)$ for concrete (x, y) pairs, and flag violations either at training time or in deployment. This aligns with proposals for verifiable constitutions that turn the question “Is AI aligned?” into the more operational question “Has this system violated its constitution?”

8.2 Limits and Open Questions

Our formalization still abstracts away several practical aspects:

Natural-language fuzziness of constitutional rules and their interpretation by LM.

Emergent inconsistencies between rules under distributional shifts not captured by \mathcal{X} in the model.

Future work might:

introduce robust or distributionally robust constitutional constraints,

integrate constitutional structures with context-aware ethical-check frameworks or multi-branch alignment architectures, or

derive sample-complexity bounds on constitutional refinement from datasets of safe examples.

9. Conclusion

We have proposed a mathematical framework for Constitutional AI by representing rule sets as predicates, defining feasible output regions, and expressing alignment as constrained optimization, this framework enables theoretical reasoning about safety guarantees and provides groundwork for further advances in mathematical AI alignment.

Funding

No

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research on the Coordination Mechanism of Trade Policy and Industrial Policy from the Perspective of Core Technology Breakthrough

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Abstract: In the context of global technological competition and industrial transformation, achieving breakthroughs in core technologies has become a critical pathway for enhancing national competitiveness. This study examines the synergistic mechanisms between trade policy and industrial policy from the perspective of core technology breakthroughs. It analyzes how these two policy instruments can be effectively coordinated to foster innovation, support industrial upgrading, and strengthen a nation's position in global value chains. The research is grounded in a review of relevant theoretical frameworks and existing literature, which highlights the interconnected roles of trade and industrial policies in shaping technological development. Through mechanism analysis and empirical investigation, the paper identifies key channels through which policy synergy influences innovation ecosystems, market access, and resource allocation. The findings suggest that a well-aligned policy framework can significantly promote technological advancement and industrial resilience. Based on the conclusions, the study proposes practical policy implications aimed at optimizing the design and implementation of coordinated policies. These recommendations are intended to provide actionable insights for policymakers seeking to navigate complex international economic environments and drive sustainable development through strategic innovation.

Keyword: Core Technology Breakthrough; Trade Policy; Industrial Policy; Policy Coordination; Innovation-Driven Development

Published: Mar 22, 2026

DOI: <https://doi.org/10.62177/amit.v2i1.1264>

1. Introduction

In the contemporary global landscape, intensified technological competition and profound industrial transformation have made breakthroughs in core technologies a pivotal determinant of national competitiveness and economic security. As of early 2026, the international environment remains characterized by strategic rivalries, supply chain reconfigurations, and the pervasive use of non-tariff barriers such as export controls and technology transfer restrictions. These external pressures have starkly exposed the vulnerabilities of nations that lack self-sufficiency in critical technological domains, often referred to as “chokepoint” technologies in areas like semiconductors, advanced manufacturing, artificial intelligence, and quantum information. This context necessitates a fundamental reevaluation of traditional policy instruments. Isolated industrial support or conventional trade measures are increasingly insufficient to address the complex, systemic challenges of fostering innovation and securing technological leadership. Consequently, there is a growing consensus among policymakers and scholars on the imperative to explore synergistic frameworks where trade policy and industrial policy are not merely parallel

tracks but are deeply integrated to form a coherent strategic response.

Building upon this background and recognizing its significance, the primary objectives of this study are threefold. First, it seeks to establish a clear theoretical understanding of how trade policy and industrial policy can functionally complement each other within the specific context of pursuing core technology breakthroughs. This involves clarifying the respective and overlapping roles of these policies in shaping innovation incentives, resource allocation, and market access. Second, the research aims to analyze the concrete mechanisms through which policy synergy influences outcomes. This includes investigating channels such as how strategic trade tools (e.g., targeted export controls, standards setting) can create a protective space for domestic industries to innovate, while industrial policies (e.g., R&D subsidies, talent programs, platform construction) build the necessary internal capacity to capitalize on that space. Third, based on the theoretical and mechanistic analysis, the study intends to derive evidence-based conclusions and propose practical policy implications. These recommendations are designed to guide the optimization of policy design and implementation, aiming to foster a more resilient, innovative, and competitive industrial base capable of achieving sustainable development in a complex international economic environment.

2. Mechanism Analysis and Empirical Investigation

2.1 Analysis of the Synergistic Mechanism: How Core Technology Breakthroughs Drive Policy Coordination

The pursuit of core technology breakthroughs fundamentally reshapes the relationship between trade policy and industrial policy, transforming them from potentially independent or even conflicting instruments into a coordinated system. This transformation is driven by the unique characteristics of core technology development, which necessitates a coherent external and internal policy environment to succeed. At its core, the mechanism is one of mutual adaptation and reinforcement, where advancements in technology create new imperatives for policy alignment, and coordinated policies, in turn, create the conditions for further technological progress.

A core technology breakthrough, such as in advanced semiconductors or artificial intelligence algorithms, is rarely an isolated laboratory achievement. Its development, scaling, and commercial viability depend on a complex ecosystem. This ecosystem requires sustained internal investment in R&D, talent, and infrastructure—a domain traditionally addressed by industrial policy. Simultaneously, it requires managing external dependencies and opportunities related to global supply chains, international standards, technology transfer, and market access—a domain governed by trade policy. The inherent interconnectedness of these needs means that a policy action in one domain directly impacts the effectiveness of the other. For instance, significant domestic subsidies for semiconductor R&D (an industrial policy tool) may be undermined if trade policies fail to prevent the outflow of key manufacturing equipment or protect the resulting intellectual property in international markets. Conversely, restrictive trade measures on technology imports intended to spur domestic substitution must be paired with robust industrial policies that actually build the requisite domestic capacity; otherwise, they risk creating supply shortages without fostering genuine innovation.

Therefore, the drive for core technology breakthroughs acts as a forcing function for policy coordination. It highlights the limitations of siloed approaches. The process can be understood through a feedback loop. The strategic goal of achieving a breakthrough identifies specific technological bottlenecks and market failures. This diagnosis necessitates a tailored industrial policy response, such as funding for high-risk foundational research or support for pilot production lines. However, the implementation of this industrial policy immediately encounters the realities of the global economic system. It raises questions about securing critical raw materials, attracting foreign expertise, exporting finished products, and navigating foreign regulatory landscapes. These challenges compel policymakers to design complementary trade policies. These might include negotiating bilateral agreements for material access, establishing export controls on nascent technologies, or actively participating in international standard-setting bodies to ensure domestic innovations gain global acceptance.

This synergy is not merely reactive but also proactive and strategic. A well-coordinated framework uses trade policy to create a “protected space” for learning and experimentation, not through blanket protectionism but through strategically managed exposure to global competition and collaboration. Meanwhile, industrial policy focuses on building absorptive capacity and

innovation within that space. The effectiveness of this coordination is amplified when policies are embedded within a broader market-based ecosystem that includes elements like intellectual property protection, fair competition, and access to venture capital. Studies on technology-intensive sectors suggest that the coupling degree between different policy subsystems—such as tax, financial, and talent policies—is positively correlated with technological development outcomes. In essence, core technology breakthroughs do not just happen because of policy coordination; they create the compelling rationale and practical roadmap for why and how such coordination must occur, aligning previously separate policy tools into a coherent national innovation strategy.

2.2 Case Studies and Quantitative Analysis of Policy Synergy in Key Strategic Industries

Building upon the general mechanism analysis, this section examines how policy synergy manifests in practice within specific strategic industries. The analysis draws on case studies and quantitative assessments to illustrate the tangible effects of coordinated trade and industrial policies on fostering core technology breakthroughs. The focus is on sectors characterized by high technological intensity, strategic importance, and significant global competition, such as advanced semiconductors, new energy vehicles (NEVs), and artificial intelligence (AI).

The development of China's new energy vehicle industry serves as a prominent case of effective policy coordination. Industrial policies, including direct subsidies for manufacturers and consumers, tax incentives, and support for charging infrastructure development, were crucial in nurturing the domestic market and building manufacturing scale. Concurrently, trade policies played a complementary role. Tariff policies facilitated the import of key components in the early stages, while later, strategic export promotion and participation in international standard-setting helped domestic champions access global markets. This alignment allowed the industry to leverage initial protection for learning and scale-building, followed by strategic engagement in global trade to solidify competitiveness. The synergy created a virtuous cycle where industrial support reduced production costs and improved technology, and open yet strategic trade engagement provided the market validation and revenue necessary for sustained R&D investment.

In contrast, challenges in other sectors highlight the consequences of policy misalignment or insufficient synergy. For instance, in areas like certain high-end manufacturing equipment or advanced materials, restrictive trade measures aimed at spurring domestic substitution were sometimes implemented without a commensurate and timely boost in industrial policy support for foundational R&D and pilot production. This mismatch could lead to supply chain disruptions without yielding the intended technological breakthroughs, as domestic capacity was not yet ready to fill the gap. This underscores the point that trade restrictions alone are not a substitute for a robust industrial innovation policy; they must be carefully calibrated and phased with internal capacity-building efforts.

Quantitative analyses, though varied in methodology, consistently point to a positive correlation between the degree of policy coordination and innovation outcomes in strategic sectors. Studies employing coupling coordination degree models have examined policy subsystems—including tax incentives, financial support, talent policies, and trade facilitation measures—within specific industries. Findings suggest that a higher degree of coupling and coordination among these policy instruments is associated with improved performance indicators, such as increased patent filings, higher R&D expenditure intensity, and faster commercialization of new technologies. For example, research on the integrated circuit industry indicates that regions or periods characterized by more synchronized policy frameworks tend to exhibit more rapid progress in moving up the value chain, from packaging and testing towards design and manufacturing of advanced nodes.

The effectiveness of synergy is further evidenced in the structure of innovation ecosystems. Policies that simultaneously address internal R&D challenges (through grants and project funding) and external collaborative opportunities (through international joint research programs or technology import agreements) tend to foster more dynamic and resilient innovation networks. The case of AI development illustrates this, where industrial policies fund basic research and talent cultivation, while trade and investment policies manage data flows, international collaboration, and the participation in global AI governance forums. This holistic approach helps in building absorptive capacity while navigating the complex geopolitics of emerging technologies.

In summary, empirical evidence from key strategic industries demonstrates that the theoretical mechanisms of policy synergy

have concrete, observable impacts. Successful cases are characterized by a sequential and reinforcing logic: industrial policies build foundational capabilities, and trade policies are then deployed strategically to secure inputs, protect intellectual property, and open markets. Quantitative assessments support the view that the coherence and integration of different policy tools are critical determinants of success in core technology domains. These insights underscore the necessity of moving beyond isolated policy interventions towards a deliberately coordinated framework tailored to the specific needs and lifecycle stage of each strategic industry.

3. Research Conclusions and Policy Implications

Based on the analysis of theoretical mechanisms and empirical evidence from key strategic industries, this study arrives at several core conclusions regarding the coordination of trade policy and industrial policy for achieving breakthroughs in core technologies. The findings confirm that isolated policy interventions are insufficient to address the complex, systemic challenges of technological advancement in a competitive global landscape. Instead, a synergistic framework where these policies are deliberately aligned in objectives, tools, and timing is crucial for fostering innovation, enhancing industrial resilience, and securing a nation's position in global value chains. The empirical case studies, particularly in sectors like new energy vehicles, demonstrate that successful technological catch-up and leadership are often the result of a sequential and reinforcing logic: industrial policy builds foundational capabilities and scale, while strategic trade policy manages external dependencies, protects nascent industries, and later facilitates global market access.

The mechanism analysis further reveals that policy synergy operates through multiple channels. It enhances the innovation ecosystem by reducing collaboration costs and aligning incentives for diverse actors, including firms, research institutions, and financial entities. It improves resource allocation by ensuring that domestic support measures are not undermined by contradictory trade flows or external shocks. Perhaps most importantly, it helps navigate the dual pressures of technological security and openness. In the current context of technological competition and supply chain reconfiguration, as observed in the period leading up to 2026, a purely protectionist or a purely liberal approach carries significant risks. Synergy allows for a more nuanced strategy that combines defensive measures to safeguard critical technologies with offensive measures to engage in international cooperation and standard-setting where advantageous.

Building upon these conclusions, the study proposes several policy implications aimed at optimizing the design and implementation of a coordinated policy framework. A primary recommendation is the establishment of stronger institutional mechanisms for cross-departmental policy coordination. Given that trade and industrial policies are often formulated and administered by different government bodies, the risk of misalignment or conflicting objectives is high. Creating permanent inter-agency task forces or councils focused on strategic technology sectors can facilitate information sharing, joint planning, and the resolution of policy conflicts. This is essential for developing a unified national strategy where trade negotiations, export controls, investment screening, domestic R&D subsidies, and infrastructure projects are all pulling in the same direction.

Furthermore, policy design must adopt a dynamic and lifecycle-oriented approach. The optimal mix and intensity of trade and industrial policy instruments change as a technology or industry evolves from basic research to commercialization and global competition. In the early, high-risk R&D phase, industrial policy support for fundamental research and pilot projects is paramount, potentially accompanied by trade policies that ensure access to critical research equipment and international talent. As technologies mature, policy focus should shift towards scaling up production, which may involve strategic protection or subsidies, followed by a greater emphasis on trade policies that promote exports, secure intellectual property rights abroad, and influence international technical standards. This phased approach prevents the pitfalls of perpetual protectionism or premature exposure to intense international competition.

Finally, the policy framework must prioritize building a robust and open domestic innovation ecosystem as the ultimate foundation for technological resilience. While strategic trade policies can manage external risks, sustainable breakthroughs depend on internal capabilities. This involves not only continued investment in R&D but also reforms in education and vocational training to develop a skilled workforce, as highlighted in the background information regarding the alignment of academic disciplines with industrial needs. Policies should encourage deeper industry-academia-research collaboration,

streamline regulations for technology commercialization, and foster a competitive market environment that rewards innovation. By strengthening these internal pillars, the nation's technological advancement becomes less vulnerable to external pressures and more capable of engaging in and benefiting from global knowledge networks on its own terms.

4. Conclusion

The significance of this research lies in its direct contribution to this critical policy dilemma. By systematically examining the coordination mechanisms between trade and industrial policies from the core technology breakthrough perspective, the study aims to provide actionable insights for enhancing a nation's innovation ecosystem and industrial resilience. The practical value is substantial. For policymakers, understanding how to align these two powerful levers can help design more effective interventions that mitigate external risks while strengthening internal capabilities. It moves beyond fragmented policy approaches towards a holistic system that can better navigate the intricate dynamics of global value chains. For industries and enterprises, particularly those engaged in high-risk, long-cycle technology development, a well-coordinated policy environment can reduce uncertainty, lower collaboration costs, and provide a more stable foundation for long-term investment in research and development. Furthermore, the research addresses a gap in the existing literature, which often treats trade and industrial policies in relative isolation, by constructing an integrated analytical framework that captures their interdependent roles in driving technological advancement.

Funding

This study was supported by the Jiangxi Social Science Foundation Project: The Synergy Mechanism of Trade Policy and Industrial Policy from the Perspective of Core Technology Breakthrough and Its Practice in China. (Grant No. 25YJ38).

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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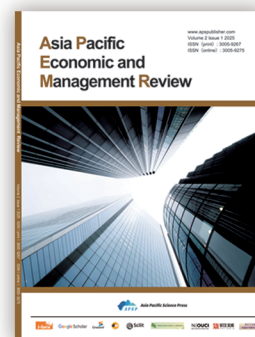
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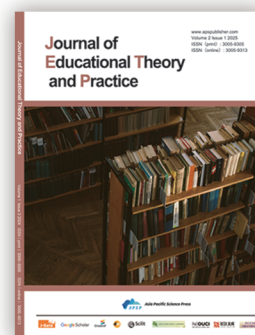
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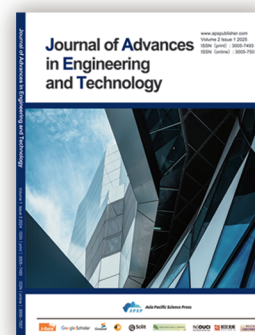
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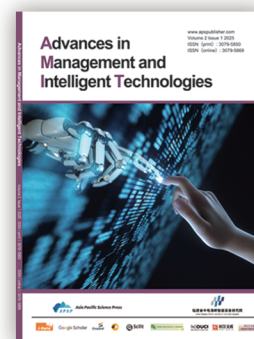
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