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Rethinking Corrosion Cost Management: Toward a Unified Framework for Indian Steel Infrastructure

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Abstract

Corrosion has emerged as a major economic and managerial concern for India's infrastructure sector, eroding between two and four percent of the nation's GDP annually. While an estimate of the world GDP in corrosion is 3.4 percent, the practice in India continues to be maintenance-focused and reactive, lacking in streamlining enforcement of standards at the technical level. The unavailability of an integrated approach of incorporating managerial frameworks and cost effectiveness continues to be a major barrier to achieving sustainable infrastructure. This paper utilizes a systematic literature review method following the PRISMA protocol to consolidate and analyse literature published between 2010 and 2025 in various academic databases. It surfaces five major thematic clusters spanning the economic burden and the lifecycle costing proactive and reactive corrosion management systems with organizational capability, control, and policy or institution framework. The study, as a result, also proposes a Unified corrosion-cost management framework and determines the variable. It also accounts for the organizational logic within governance and decision-making framework. In doing so, the frameworks shift the paradigm from corrosion control being a maintenance routine to strategic management. It establishes the rationale for conducting national corrosion audits and subsidized CMS, the central database on corrosion-cost, to be institutionalized in India with the expectation of improving sustainability, cost effectiveness, India's infrastructure for greater dependability.

Keywords: Corrosion Management System, Life-Cycle Costing, Preventive Maintenance, PRISMA, Infrastructure, India, Sustainability

JEL Codes: L61, H54, and Q56

1. Introduction

Steel forms the basis of the global economy while enabling the transportation, energy, water, and construction industries. Unfortunately, the long-term durability and sustainability of steel is under constant threat of corrosion—an economic process that deteriorates metal surfaces which come into contact with water, salt, or pollution. The corrosion particular AIM, which equates corrosion with lost money and productivity, has been calculated at US $2.5 trillion, which is 3.4 percent of the world GDP. Studies show that with the addition of proper preventive maintenance strategies, we find that 15 to 35 percent of that loss could be prevented (NACE, 2016).

India's problem appears alarming too. The Council of Scientific and Industrial Research – National Metallurgical Laboratory (CSIR-NML) has stated that corrosion alone accounts for a 2-3 percent annual deficit of our GDP (Avenue Mail, 2025). Other estimates are considerably larger, for example, a 2025 report by DT Next placed the losses due to corrosion to ₹12 lakh crore yearly (DT Next, 2025) and the International Zinc Association has reported that India loses 5-7 percent of GDP due to corrosion (Business Standard, 2021). The disparity in these figures showcases the lack of uniformly accepted corrosion-cost accounting, and more importantly, the lack of comprehensive policy and managerial integration pertaining to the issue.

Corrosion also has severe ramifications on safety and the environment. The disruption that comes from the failure of pipelines, bridges, power plants, and industrial equipment, comes at a hefty price. Not only do these failures put lives at risk, but also, cause service disruption and material waste which, in turn, leads to pollution (Society of Chemical Industry, 2013). The 'hidden' costs of these failures, which involve downtime, lack of energy, and early replacement of components, lead to even more severe economic consequences.

Most Indian infrastructure organizations tackle problems once they occur, which is called a reactive maintenance model, and ignore taking steps beforehand a more preventive approach. Such issues occur due to split accountability, a lack of central data, imperfection in inspection standards, and planning budgets weakly (Economic Times, 2023). Hence, managerial problems evolve from mere technical corrosion control to envelop finance, governance, and managerial planning, and intersectoral coordination. The international frameworks, which also integrates corrosion control, commends the principles of life cycle costing (LCC) and asset management frameworks, with overarching sustainability and ESG (environmental, social, and governance) principles (NACE International, 2016). Corrosion management and control in India, on the other hand, is still in a silo, a mere maintenance activity.

This gap is what this paper intends to fill. It conducts a systematic literature review (SLR) using PRISMA guidelines. To develop the Unified Corrosion-Cost Management Framework, a synthesis of 36 peer-reviewed works published from 2010-2025 was done. The Unified Corrosion-Cost Management framework integrates governance organizational, life cycle costing exposure environmental, and maintenance preventive, to reposition corrosion control as a strategic function to enhance India's sustainable infrastructure development and fiscal efficiency.

2. Research Methodology

This research utilizes a Systematic Literature Review (SLR) focusing on the guidelines set in the Prisma framework (Page et al., 2021). The SLR framework is opted for due to the ability to methodologically distinguish, as well as structure the evidence regarding the strategic corrosion-cost estimation framework, corrosion management, and life-cycle costing, and bring in evidence SLR recognizes policy and management literature. It aims to assimilate available literature in India and across the globe that recognizes corrosion as not only a technical issue, but also a managerial, economic, and policy issue that can affect the management of infrastructure sustainability.

The review focuses on publications from January 2010 to March 2025 and aims to comb across four key databases, Scopus, the Web of Science, Science Direct, and Google Scholar, to adequately balance industry and research perspectives. Specialized Search strings were constructed based on Boolean operators and refined over multiple iterations of initial searches. The final search set included the terms: "corrosion cost", "economic impact of corrosion", "corrosion management system", "life-cycle cost", "India", "preventive maintenance", "asset management" and "infrastructure corrosion". This set is focused on literature that enhanced the managerial and financial portfolio concerning corrosion of assets.

The manuscripts being considered needed to be published in English, peer-reviewed, and cover economic, organizational, or policy areas relating to corrosion. Papers on corrosion management, cost estimation, preventive maintenance, and life-cycle costing were retained. Other papers focusing on management-less laboratory work, editorials, duplicates, non-scholarly commentaries, and electrochemical testing and materials science were also excluded.

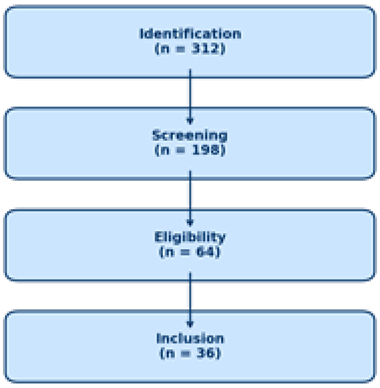
The systematic search retrieved 312 articles in total. Once duplicates were removed, and the papers were screened, 198 papers emerged. The number grew smaller with the decreasing number of abstract and title evaluations–64, and then 64 full-text studies, out of which 36 articles met all criteria and were selected for synthesis. Compliance with the process was done according to PRISMA's four stages: Identification, Screening, Eligibility, and Inclusion. The process adhered strictly to PRISMA's four stages—Identification, Screening, Eligibility, and Inclusion—as illustrated in Figure 1.

Table 1. PRISMA Flow Summary of Literature Selection

PRISMA Stage	Description	Records
Identification	Records retrieved from databases	312
Screening	After duplicates and non-English records removed	198

Eligibility	Full-text articles assessed for relevance	64
Inclusion	Studies meeting all inclusion criteria	36

Figure 1. PRISMA 2020 Flow Diagram for Study Selection



Note: The figure depicts the number of records identified, screened, excluded, and finally included in the review, following the PRISMA 2020 guidelines.

The 36 selected studies were analyzed using NVivo 14 software for systematic coding and identifying themes. Each paper was scrutinized for its research objectives, country or region of study, methodology, and findings. Thematic coding resulted in five dominant clusters: 1) economic estimates of corrosion: quantifying GDP and sectoral sinks; 2) corrosion management systems (CMS): governance, inspection, and monitoring; 3) life-cycle costing (LCC): maintenance and financial planning; 4) preventive versus reactive maintenance: long-term efficiency; and 5) policy and institutional mechanisms: national and organizational responses.

To improve reliability, two researchers independently repeated the search and coding process, and differences were solved through discussion. Pragmatic cross-database triangulation and compliance to PRISMA frameworks ensured procedural correctness (Tranfield et al., 2003; Snyder, 2019). While a lack of access to proprietary or grey literature may have been apparent, the systematic selection of peer-reviewed sources provided a solid evidential foundation. Such a comprehensive methodological approach substantiates the Unified Corrosion-Cost Management Framework, which is proposed in the following section.

3. Literature Synthesis

The international literature regards corrosion not just as a problem of materials, but more as one of macro-economics, safety and governance. That the IMPACT program by NACE International brought forth multi-sector evidence estimating a global loss around SU$2.5 trillion (approximately 3.4% of the global GDP) and argued that 15–35% of such losses could be avoided through management practices implemented as part of an organization-wide management system, is more than worrying (NACE International, 2016; Inspectioneering, 2016). The broad country level updates do not differ much: for the case of the United States, subsequent analyses tied to the IMPACT work continue to place annual corrosion costs around three percent of GDP when direct and indirect costs are summed up (NACE International, 2016).

The estimates of India's economic burden might differ with each source, but the numbers are still significantly concerning. While an industry report claimed the country's losses these past few years amounted to about 3% of the GDP, the National CSIR-NML claims it could be as high as 4% (Avenue Mail, 2025; DT Next, 2025; Business Standard, 2021). These estimates are usually incorrect due to the lack of a unified national database, fragmented over multiple ministries, public sector undertakings, contractors, and other institutions. Regardless of the source, the estimates always indicate a severe economic burden, and the lack of cross project data severely limits benchmarking, budgeting, and allocation of funds toward preventive measures.

Formal interdisciplinary Corrosion Management Systems (CMS) integrate the engineering aspects of corrosion control with associated governance, budgeting, and other decision-based processes. Double digit savings over a portfolio are realizable when a CMS strategy is applied with the practices of corrosion control, a coated asset, and competency development (NACE International, 2016). These savings are multiplicatively enhanced when corrosion is integrated into the asset maintenance strategy, as opposed to being managed as an isolated set of tasks, and are coupled with the company's strategic silos and key performance indicators (Inspectioneering, 2016; NACE International 2016).

Another preventive and reactive maintenance contrast stream outlines the proactive interval study records ("Proactive Inspection Intervals…"). Interval studies of proactive inspection along with condition monitoring and timely recoating indicate that the services and life failure probabilities improve, while the contrary signals unattended degradation with enforced outage penalties plus safety and incident signals (Tamimi et al., 2024; Lawal et al., 2023). While such conclusions might seem intuitive, equivalent conclusions with empirical relevance serve public budgets: moving from "fix after failure" to "predict and prevent" shifts cash flows from unplanned shutdowns to lower variance, planned expenditure reduction and net embodied carbon reduction from avoidance of premature, cyclical replacement (Tamimi et al., 2024).

Life-cycle costing (LCC) serves as the financial metrics integrating the insights offered by the model. Rather than concentrating on minimizing capex, LCC models the price of performance of the coating systems, performance of the systems, inspection frequency, access logistics, and risk as part of the total cost of ownership over an extended period. LCC analyses, at the stages of design, procurement, and rehabilitation, have become mandatory for international infrastructure projects pertaining to transport, energy and water, which further justifies the case for prevention on an discounted over asset life (NACE International, 2016) In the case of India, LCC appears to be adopted by only a few public corporations and some private operators, as the literature and industry discussion suggests, which does not allow a systematic comparison of alternatives, thus reducing the incentives to invest in durability at the design stage (Avenue Mail, 2025; Business Standard, 2021).

The findings from management studies are supported by the functioning of these policies across borders and regions. Japan and South Korea are often mentioned and praised for their discipline of specification, scheduled mandated intervals of inspections, and centralized technical guidance. These factors result in consistent execution and visibility of data across owners and regions. In contrast, the practice in India remains 'patchy.' With abundant standards existing, there remains the inconsistency of enforcement, competent pipelines, intra-agency data sharing, and low standards of surface preparation. There are also low standards of coating, weak inspection documentation, and unreliable surface preparation. There are numerous calls for a home-grown standard of practices in national corrosion-cost programs, with the aim to standardize definitions, publish and collect statistics, and tie public funding to compliant CMS programs, along with compliant LCC decision making (NACE International, 2016; Avenue Mail, 2025).

All the evidence discussed together leads one to reason with managerial logic. In the first place, the economic burden seems to be large enough to deserve national interest. Secondly, if organized through a CMS, practices of a preventive nature, are available to be spent against LCC and not just one-year budgets. Finally, the institutional mechanisms of audits, training, and mandatory reporting, are the levers that turn technical knowledge into sustained financial and safety outcomes. It is the first three outcomes, that provide reason and motivation for the next unified structure that will be proposed. This structure will be created by the governing, budgeting and management framework relative to the exposure of engineering control at the environment and the infrastructure that is steel intensive in India.

4. Proposed Unified Framework

A synthesis with relevance to corrosion and the NACE International (2016) study coupled with the CSIR–NML (2025) study in the Indian ban, enables the construction of the Unified Corrosion and Cost Management Framework (UCCMF) and for strategic corrosion and cost management, poised in an 'integrated technical, organizational, and financial nexus of prevention and accountability.' Corrosion management strategy for multinational corporations operating in diverse and emerging markets should include a UCCMF as a strategy for integrating corrosion and cost management across the organization as well as for the rational allocation of organizational resources, UCCMF, for strategic corrosion and cost management.

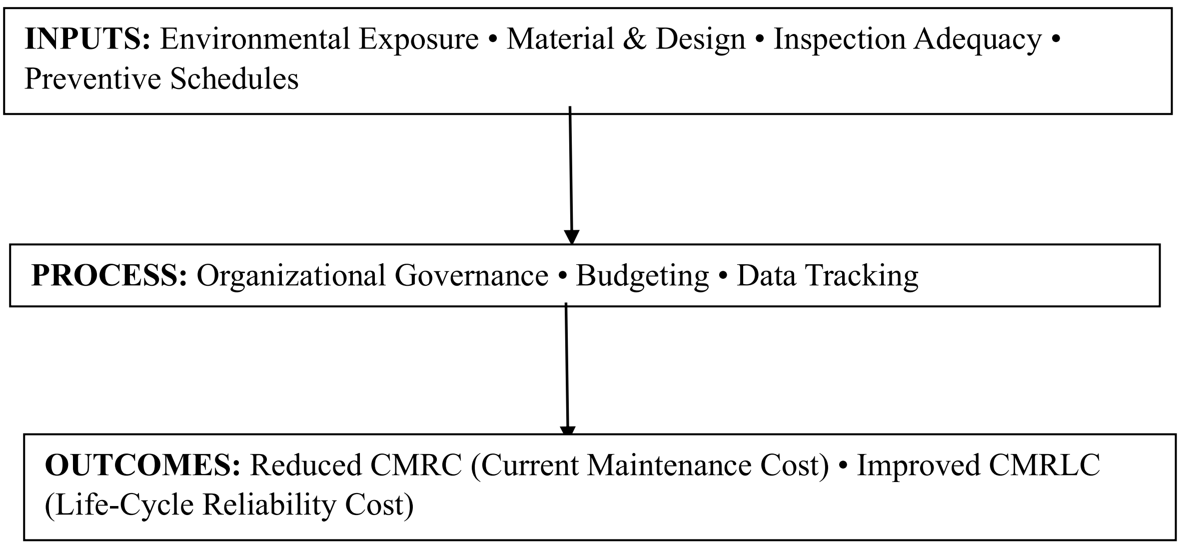
The strategic role of integrating corrosion management with rational cost allocation must be underscored, as with most frameworks, the UCCMF Framework rests on a synthesis of the Corrosion Management Systems (CMS), Preventative Maintenance (PM), and Life-Cycle Costing (LCC) Policy Frameworks. Costing on a Life Cycle basis is a method for allocating organizational resources for managing assets over an extended period to achieve a set of business objectives. Predictive Maintenance Frameworks encourage rational expenditure for preventive capability and the management of capability risks.

Moreover, the UCCMF Internal Policy measures include inputs and data on the relevant cost estimates and corrosion rates and scope, the aggressiveness of the environment, material selection, composite design, structural detailing, and coatings specification knitted and constructed. Coupled with the above factors, the relevant scope and estimates protect interoperability.

The process layer operationalizes these inputs through three inter-linked subsystems—organizational governance, budgeting and financial control, and data tracking and feedback. Governance allocates responsibility matrices and audit and compliance mechanisms; budgeting incorporates for preventive expenditure in life-cycle financial plans; and data tracking feeds field data for analytics and continuous improvement. Together, these subsystems transform corrosion prevention from a mere project activity to an enterprise-wide managed process.

The outcome layer measures performance with two financial indicators—Current Maintenance and Repair Cost (CMRC), which denotes annual expenditure on reactive maintenance, and Cumulative Maintenance Reliability Life-Cycle Cost (CMRLC), which denotes the optimized long-term cost, factoring in reliability and service life. A decrease in CMRC and an increase in CMRLC indicate a better shift in terms of sustainability and fiscal efficiency. Over and above, organizations embracing this unified system are expected to achieve lower total ownership cost, diminished structural failures, and significant reductions in GDP loss suffered through national corrosion and fiscal efficiency. The framework thus shifts the definition of corrosion control to a cross-disciplinary function of strategic management, marrying governance intelligence with engineering data. For Indian infrastructure agencies, this framework offers a structural pathway to international best practice with the integration of corrosion performance in ESG, sustainability, and risk-management reporting.

Figure 2. Unified Corrosion-Cost Management Framework



5. Discussion

These results from the study corroborate that corrosion is no longer just an engineering concern. It is also a matter of concern in strategic management with respect to productivity, infrastructural dependability, and economic efficacies of a nation. The gradual degradation of infrastructure in India spills a lot of money, almost two to four percent of the GDP. This calls for prompt institutionalization and preventive, data driven systems (CSIR–NML, 2025). Although the loss is substantial, the data loss phenomenon is far less than in global systems, measuring around 3.4 percent of world GDP

(NACE International, 2016). This paradox arises mainly from India's lacking systemic controls and its reactive-oriented culture towards maintenance.

Other global countries such as Japan and South Korea as case studies show that corrosion costs can also be mitigated to a certain extent from the centralized specifications and mandatory inspections along with a national corrosion database. For these countries, managing corrosion is as important as managing infrastructure. It is a central piece and not a peripheral idea in governance. India, on the other hand, suffers from "pouring rain" syndrome. The institutional arrangements taken such as disparate across ministries and project owners för fricative designed, irregular inspections, petty record maintenance, and quality assurance. This maintenance culture adds to the reactive maintenance costs and lowers asset prices.

The proposed unified framework interface engineering with financial and governance mechanisms software and directly addresses this gap. In doing so, it transmutes corrosion control from a localized process to one that seamlessly integrates with organizational wide budgeting, auditing, and data systems. These systems, in turn, enable organizations to shift maintenance from a reactive strategy to one that is more proactive. This shift, coupled with the ability to fund and track spending, results in an optimized organizational governance structure. The proposed framework uses CMRC and CMRLC as key performance indicators to monitor organizational performance. If these metrics are achieved, organizational performance, as measured against other similar structures, as well as economic and environmental performance at a national level, improves significantly, and the benefits are not confined to individual projects.

From a managerial perspective, the framework being proposed integrates the other pillars of sustainability and risk governance to more traditional approaches in corrosion performance management. When embedded within a long term organizational financial framework, resource allocation to more cost-effective planned maintenance strategies improve net resource productivity of governance structures and systems. Empirical studies indicate that such strategies can extend asset life and the total maintenance cost by more than twenty percent, however as NACE International (2016) highlight, these gains are contingent upon the level of data driven visibility, technical ability and the leadership willingness to commit organizational and financial resources.

The strategic importance of integrating corrosion control with sustainability and ESG compliance is enhanced even further. The Climate and Resource goals are achieved with every ton of steel saved through prevention as it diminishes the energy and emissions associated with new production. There is a new trend with global investors and infrastructure funds assessing the compliance of ESG standards to the requisite material durability of concrete. The adoption of a national corrosion-management framework will put India ahead of the curve with respect to these changes.

A shift from reactive to preventive maintenance will require a unified national approach. This will include the development of a data base of corrosion costs, the mandatory auditing of corrosion in publicly funded infrastructure and the development of training programs to enhance the managerial and technical skills to implement these changes. Digital technologies, in the areas of real-time inspection reporting, predictive maintenance, and the sharing of data across governmental agencies, also have a critical role to play. These changes will transform the unified framework from an abstract concept to one that is actionable, with the promise of great accountability and savings.

In contemporary times, the unified framework of corrosion management should be positioned as a core element of strategic governance to enhance the organization's value, rather than technical maintenance. With the unified framework contextualized across public and private infrastructure, India will minimize systemic deficiencies, bolster fiscal responsibility, and reinforce its sustained commitment to infrastructure development.

6. Policy and Managerial Implications

In as much as this study is conceptual, the unified corrosion-cost management framework (UCCMF) has much to offer for the development of policy and the practice of management. The framework integrates corrosion control with governance, budgeting, and visibility of data, which suggests a corrosion preventive maintenance policy that moves far beyond the engineering domain descriptive of how institutions can reconceptualize preventive maintenance as a routine tactic of national and organizational strategy.

In the case of the policy framework, the UCCMF highlights the necessity of underlying institutional mechanisms that marry corrosion management with the governance of infrastructure. At the conceptual level, a national database or registry of corrosion-related losses can serve as the spine of information that enables policymakers to gauge the level of sectoral exposure, benchmark preventive expenditures, and craft data-driven regulations. It is also implied that the effectiveness of policy is not only a function of the level of technology, but also the internalization of responsibility where the expenditure on preventive measures is considered as an investment rather than a cost.

The framework allows managers and decision-makers to assess corrosion performance differently, now viewing organizational resilience, as well as financial prudence, and performance as equally intertwined and balanced. Managers should be embedding corrosion control within risk management and sustainability systems as part of ESG aligned strategies, and major infrastructure resilience frameworks. Instead, both CMS (Corrosion Management Systems) and Life-Cycle Costing (LCC) should be treated not as operational routines but rather as decision-making strategies to be eschewed when material reliability is deterministically and reflexively coupled with financial and reputational engendering.

The framework fundamentally requires organizations to replace entrenched short-term maintenance budgets with far more valuable life-cycle governance models. This shift in maintaining control systems, or in control over maintaining and regulating resource systems, relative to the life cycle of the entities they govern allows more anticipated reliability, and reconstructing economics from failure models more historically, than recurrent integration from the past 20 years. In this, corrosion management lies far more within the realm of 'preventive governance' than 'governance' where governance becomes the management of reactive practices for more strategic forecasting.

Corrosion management, framed within the strategic context of India's development of green infrastructure and climate resilient strategies framed externally, becomes a strong pointer towards the country's goals of sustainability as well. This section justifies the need to develop a set of strategies and policies to reduce the corrosion losses.

Thus, the UCCMF provides decision-makers and planners with a model of structured reasoning that aids in the understanding of how the preventative strategies, data systems, and governance mechanisms of the model derive and sustain, in fiscal, and sustainability outcomes. These conceptual relationships foster the rethinking of the management of infrastructure as a rational, ecological, and political multi-tiered system.

7. Conclusion

This research aims to shift the definition of corrosion management from the reactive technical exercise approach to a managerial and financial process. With the aid of scoping literature review and synthesis of global and Indian evidence, this research developed the Unified Corrosion-Cost Management Framework (UCCMF). This framework incorporates Corrosion Management Systems (CMS), Preventive Maintenance (PM), and Life-Cycle Costing (LCC), assuming a central management governance structure. This framework illustrates how organizational responsibility, funding, and performance measurement to account for the environmental, material and design factors can bound corrosion prevention to a strategic decision domain. This shift adds to the corrosion management literature by providing a framework with a governance lens needed for a developing country.

The framework, in widening the discourse on corrosion from a governance and economic management lens, situates it within the context of infrastructure sustainability. It demonstrates, for instance, that superior materials are not the only determinants of high asset longevity and low maintenance; rather, they are the result of thoughtful design, committed leadership, and integrated amenable governance. The framework thus offers a rationale to policymakers and managers to shift from reactive to preventive, data-driven maintenance.

Theoretically, this study contributes to the field of corrosion management by broadening the scope beyond engineering toward interdisciplinary management science. Practically, it highlights the need for collaborative cross-sector institutions to centralize data and assume accountability for performance, as this is critical for the sustainability of India's infrastructure. While the framework remains abstract, its rationale provides a starting point for further empirical studies to ascertain the relationship among CMS, preventive expenditures, and life-cycle cost savings.

Further, the management of corrosion should be reconceived as a means to enhance national competitiveness and sustainability. The adoption of the UCCMF model in institutional policy and industry practice would not only curb the excessive financial drains but also position the infrastructure governance of India alongside world leaders in operational efficiency, resilience, and ecological stewardship.

8. Suggestions for Future Research

While the current document is research based, it does suggest several potential areas for new empirical research and theory development. Future studies may attempt to operationalize the Unified Corrosion-Cost Management Framework by defining measurable indicators for its components: governance, data systems, preventive investment, and life-cycle cost optimization. Empirical research may utilize structural equation modelling or multi-level regression to assess the causal relationships among these constructs within the infrastructure sectors of transportation, energy, and manufacturing.

Further research could investigate the impact of the adoption of corrosion management systems on the long-term maintenance costs and maintenance cost reliability of assets. Comparisons of Indian organizations with international peers could provide cross-cultural perspectives on the influence of institutional development, legal regulations, and climate on the effectiveness of preventive maintenance.

Employing a mixed-methods approach may yield insights into the more complex frameworks of decision-making in the control of corrosion through the use of archival sources and expert interviews. Moreover, the modelling of corrosion-risk behaviours and corresponding managerial and policy actions could be strengthened through the use of big data and predictive AI analytics, providing currently unavailable insights into corrosion-risk behaviours.

In framework expansion, scholars may start tying corrosion management with sustainability transitions, circular economy models, and even the ESG reporting frameworks. Such cross-cutting collaboration can situate corrosion studies within the broader conversations surrounding sustainability and operations research. Subsequent research can also delve into more behavioural and organizational aspects—how a leader’s perception of risk, along with the organizational design of incentives, shapes and drives preventive decisions.

These next steps of research should test the theoretical rationale outlined on this paper and develop a rich empirical evidence base on the economic, environmental, and governance aspects of unified, integrated management of corrosion costs. Such work will translate the ideas brought forth in this paper into tangible, actionable policies surrounding resilient and sustainable infrastructure.

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