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STRATEGIES FOR MITIGATING ENVIRONMENTAL IMPACTS AND ASPECTS: FROM REGULATION TO GREEN SUPPLY CHAINS, DIGITAL MONITORING AND URBAN NATURE-BASED SOLUTIONS

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Abstract

Background: Industrial and urban development intensifies emissions, energy use, water consumption, waste generation and residual exposure, requiring mitigation approaches that move beyond isolated compliance. **Aim:** This study evaluates how environmental regulation, green supply-chain governance, digital monitoring and nature-based solutions can reduce environmental aspects and impacts when applied separately and as an integrated portfolio. **Methodology:** A qualitative integrative review was combined with a coded evidence matrix of 150 industrial and urban-interface observations across five regions, eight sectors and five mitigation bundles. Outcomes were assessed through emissions, energy, water and waste reductions, payback period and composite environmental performance. **Results:** Across all observations, emissions fell by 22.0%, energy use by 22.8%, water use by 15.2% and waste by 21.6%. Integrated strategies produced the strongest results, achieving 31.8% mean emissions reduction, 31.4% energy reduction, 29.7% waste reduction, a 98.7 performance score and a short 1.21-year payback. Digital maturity and sensor coverage strengthened performance, while procurement and supplier audits extended mitigation upstream. **Conclusion:** Environmental impacts are mitigated most reliably when regulation, procurement, digital evidence and urban ecological buffering operate together as one evidence-driven management system. The findings support portfolio-based policy and management, reducing impact shifting while improving operational, financial and environmental outcomes across diverse sectors.

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1. INTRODUCTION

The industrial and urban growth has brought material welfare but as well as contributed to the escalation of the environmental factors including air emissions, wastewater discharge, energy demand, resource depletion, hazardous waste and land-cover change. To use the terminology in this paper, to organisations, I view environmental aspects as the controllable activities/interfaces, where organisations interface with nature, and environmental impacts as the measurable changes that ensue in air quality, climate forcing, ecological condition and human exposure. That difference is important since mitigation is not often attainable through the use of an individual instrument. The manufacturing evidence, trade and urban studies demonstrate impact reduction, where the rules, markets, procurement systems, monitoring technologies, ecological infrastructure are focused on quantifiable environmental results and not on symbolic promises (Greenstone, 2002; Becker and Henderson, 2000; Fowlie et al., 2012; Shapiro and Walker, 2018).

The initial strategic direction is regulation. Traditional descriptions occasionally have environmental regulation as a compliance cost, but the empirical literature is less unidimensional. Evidence on-plant evidence in the United States Clean Air Act indicates that the nonattainment designation has altered the polluting industrial activity and provided actual costs of pollution to pollution-intensive firms and subsequent work illustrates that stricter implicit costs of pollution are a key determinant of the long-term fall in manufacturing emissions in the United States (Greenstone, 2002; Shapiro and Walker, 2018). In instances where the credibility of monitoring and enforcement is true, market-based instruments can minimise the emissions: when the Southern California RECLAIM programme increased control over facility NOx emissions compared with equivalent control, but also attracted distributional accountability concerns (Fowlie et al., 2012). Some international evidence also indicates that environmental costs have the potential to alter trade patterns but the extent is determined by the mobility of sectors, the type of abatement technology and the institutional enforcement (Levinson and Taylor, 2008; Hanna, 2010). Policy can therefore best be effective when it is enforceable, transparent and linked to operational data.

This combined framing also indicates the way the environmental management systems are practiced in reality. A factory can meet a permit, but continue to cause unavoidable effects by making inefficient buying choices, inefficient maintenance, unscreened suppliers or a paved lot that promotes stormwater run-off. On the other hand, a city can also invest in green infrastructure, although the payback will be incomplete until industrial emissions and logistics choices keep exposing the same neighbourhoods. A mitigation research paper must thus bridging the source, pathway and receptor of harm to the environment. The industrial process or supply-chain decision is the source, the physical or organisational route through which the pollution waste or resource demand is passed and the receptor is the worker, community, ecosystem or urban infrastructure that is impacted by that passage. This source-pathway-receptor logic renders it feasible to determine whether any strategy just changes impacts or actually minimizes them on a system level. It is also useful in cross country and cross sector comparison in that the same rationale can be applied to a steel plant, supplier of electronic parts, a logistics network or urban redevelopment programme without the loss of the difference between activity, aspect and impact.

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The second route is the greening of supply chains, since a significant portion of the impact of industry lies outside of the immediate scope of the attention of the focal firm. Empirical data on Chinese, British and international manufacturers indicate that green purchasing, supplier collaboration, eco-design, reverse logistics and internal environmental management are linked with better environmental performance especially when the supplier pressure is coupled with supplier capability-building (Zhu et al., 2008; Zhu and Sarkis, 2004; Holt and Ghobadian, 2009; Vachon, and Klassen, 2008). Other more recent survey data associate both cost and customer drivers to internal and external green practices, and relates green human-resource practices to green supply chain management and sustainable performance (Wang et al., 2018; Zaid et al., 2018). Such results have redefined a focus on end-of-pipe treatment to procurement requirements, design specifications and an inter-firm learning.

The third channel is digital surveillance. Contemporary industries tend to employ sensors, enterprise data platforms, big-data analytics, digital twins and automated reporting to identify and locate leaks, optimize energy requirements, track materials and ensure compliance. Digital tools minimise effects of technological determinism: the use of technology in management routines, maintenance choices and sustainability measurements should be adopted in order to minimise the impact. Nonetheless, empirical studies on Industry 4.0 technologies and green operations reveal that digital capability has the potential to boost sustainable performance in terms of green-based operations, whereas big-data analytics can enhance healthier green supply-chain performance in the form of green innovation and integration of suppliers (Kamble et al., 2020; Gupta et al., 2021; Javaid et al., 2022; Abdul-Rashid et al., 2017; Bag et al., 2021). Digitalisation thus acts as a medium that renders the environmental factors transparent, comparable and fixable.

Lastly, mitigation should encompass the urban systems getting, enhancing or alleviating the industrial effects. When planned as infrastructure (not an amenity), nature-based approaches to runoff reduction like urban forests, parks, wetlands, green roofs, bioswales and permeable landscapes can lower temperatures on surfaces, sequester carbon and enhance air quality. Empirical and modelling research on urban climate adaptation demonstrates the ability of green infrastructure to modify energy exchange and hydrology but the systematic evidence supporting the role of urban greening as a mechanism to produce measurable cooling benefits remains (Gill et al., 2007; Bowler et al., 2010; Armson et al., 2012; Demuzere et al., 2014; Raymond et al., 2017). The research question that will be applied in this case is an integrative one: how can policy, supply-chain governance, digital monitoring and nature-based urban design be integrated to reduce any negative effects in the modern industries in a measurable, institutionally practicable, and replicable transferable way?

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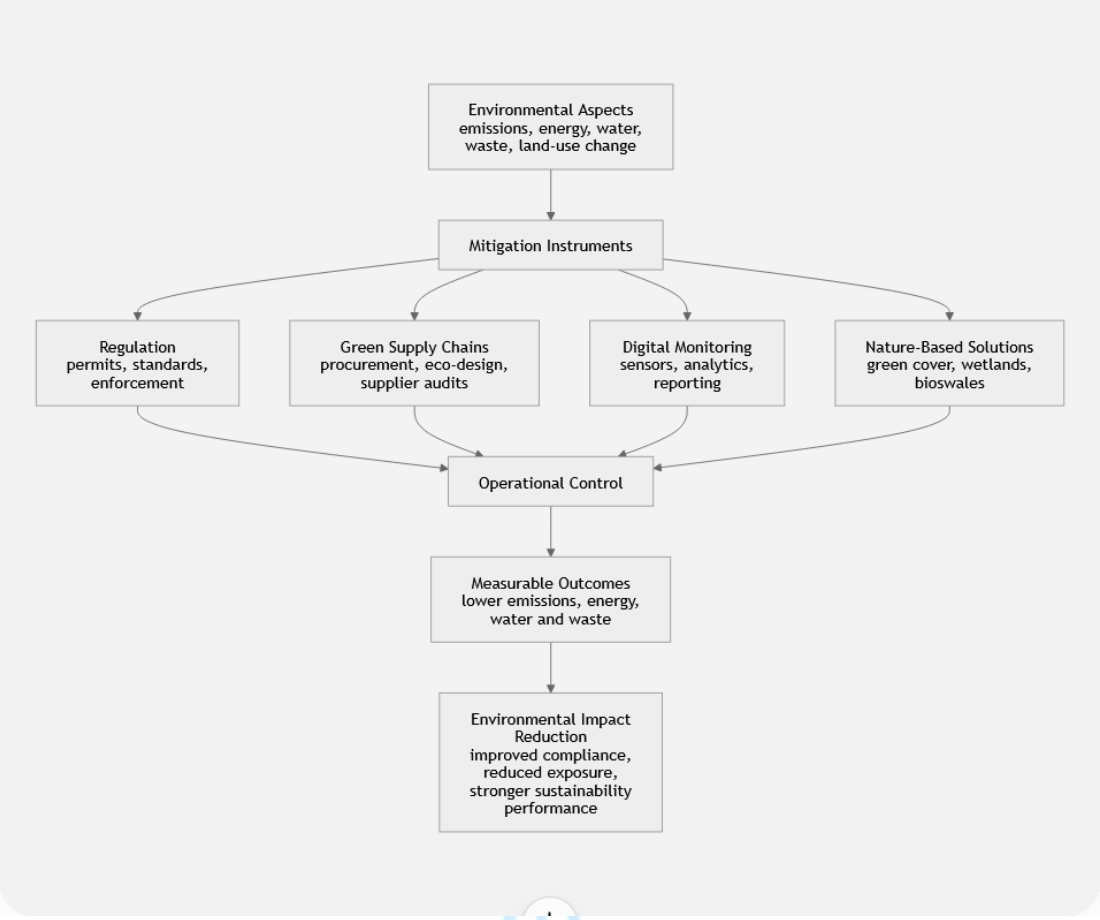


Figure 1. Conceptual framework linking mitigation instruments to measurable environmental impact reduction.

Table 1. Strategic pathways for mitigating environmental aspects and impacts.

Mitigation strategy	Main environmental aspects controlled	Primary benefit indicator
Environmental regulation	Permits, emissions limits, abatement obligations, market caps	Reduced emissions intensity and improved compliance
Green supply chains	Supplier selection, eco-design, reverse logistics, materials sourcing	Lower embedded waste, energy use and pollution
Digital monitoring	Real-time sensors, analytics, reporting, predictive maintenance	Faster detection and operational correction
Nature-based solutions	Impervious surfaces, urban heat, stormwater, residual exposure	Cooling, runoff reduction and local ecosystem services

2. LITERATURE REVIEW

Causal evidence in the literature on environmental regulation has the best causal evidence as most studies use policy discontinuities. Becker and Henderson (2000) demonstrated that the regulation of air quality affected the location of polluting plants and Greenstone (2002) estimated that Clean Air Act nonattainment status cost employment, capital and output in industries which produced a pollutant. The results support the conclusion that regulation changes firm behaviour, but also reveal the importance of

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impact mitigation being evaluated against environmental outcomes and economic adjustment. Shapiro and Walker (2018) subsequently broke down the reduction in the manufacturing air pollution in the United States and discovered that regulation, rather than trade or productivity had most of the impact on those emissions. The topic of market design was contributed by Fowlie et al. (2012), who demonstrated that RECLAIM reduced NOx emissions compared to a non-experimental control group without the establishment of apparent demographic differences in NOx changes. Complicating the picture, Levinson and Taylor (2008) and Hanna (2010) reported pollution-haven and outward-investment responses, meaning that the impacts of regulation can be shifted to weaker linkages when supply chains are weakly regulated.

A learned lesson of measurement emerged in the literature of regulation as well as succeeding lines of research. Observable outcomes used in policy evaluation, which included plant entry, output, emissions or abatement cost were more than management studies, which frequently employed use of perceptual survey measures of environmental performance. Both methods proved to be useful, and both proved to be weak. Facility-level designs provided causal identification with more robustness, however, there were some that under-characterized managerial mechanisms. The underlying mechanisms of supply-chain and digital studies described managerial phenomena but frequently did not include valid environmental premises. A developed mitigation system must thus have involved the causal art of policy assessment as well as the organisational specifics of operations research. That is why the current review did not prioritize strategies based on the reported benefits and accepted both good quality of evidence and context of implementation. It also assisted in the prevention of considering adoption, certification or ownership of technology at the same level as at-verified environmental improvement.

The second stream is a look at voluntary and inter-organisational mitigation. Zhu and Sarkis (2004) discovered that initial green supply-chain management users in the Chinese manufacturing sector correlated operational practices to eco-performance and cost efficiency and Zhu et al. (2008) tested a multidimensional measurement model through internal management, green purchasing, customer cooperation, eco-design and investment recovery. Vachon and Klassen (2008) found that environmental collaboration over supply chains related to manufacturing performance and Lee and Klassen (2008) found that supplier case studies revealed that involvement by buyers proved to develop the environmental capabilities of small and medium suppliers. According to Holt and Ghobadian (2009), the adoption by the UK manufacturers was not even but was meaningful. The study of Green et al. (2012) revealed that green supply-chain practices enhanced the organisational performance, in terms of environmental performance, and Wang et al. (2018) demonstrated that both customer and cost pressures impacted both the internal and external green practices. Zaid et al. (2018) further contributed that both green HRM and supply-chain practices contributed to sustainable performance, implying that organisational culture and skills are required in procurement systems.

The discussion of sustainable procurement also emphasises constraints. The investigations invariably indicate that the selection of suppliers, eco-design and reverse logistics, have an influence, but it is contingent on the quality of the audits, transparency of data, supplier power and long-term cooperation.

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Suppliers might view compliance as a documentation towards the buyers when the suppliers themselves request the buyers to provide them with environmental requirements that are not of technical assistance. Collaborative capability-building, in turn, has the potential to transform environmental aspects into objects of innovation. This can be observed in empirical studies related to the integration of green suppliers, big-data analytics and performance: Bag et al. (2021) theorized that the performance of the supply chain with the help of analytics enhances sustainable performance, whereas subsequent studies in manufacturing discovered that the performance of big-data analytics increased the performance of the green supply-chain with the help of green innovation and technological intensity (Al-Khatib, 2022). These investigations suggest that sustainable procurement is not just a buying policy; but an information structure to discover, prioritize and limit encoded effects.

Digitalisation literature is more recent and disjointed, but it is gaining more and more relevance to mitigation practice. In a study analyzing sustainable manufacturing processes, Abdul-Rashid et al. (2017) observed that sustainability performance was linked to sustainable manufacturing practices, and research on Industry 4.0 has since investigated how sensors, cyber-physical systems, analytics and digital twins alleviate operation decisions. Kamble et al. (2020) related Industry 4.0 technologies to sustainable performance in the form of sustainable operations, whereas Gupta et al. (2021) created an evaluation framework that links Industry 4.0, cleaner production, and circular economy performance. The synthesis of the potential capability of digital technologies to complement circular economy measures created by Javaid et al. (2022) is supported by empirical research that heightens the possibility of lessening emissions without showing evidence of the existence of data systems. They are most useful enhancing measurement frequency, maintenance timing, energy optimisation and traceability. Thus, digital instruments ought not to be considered as replacement of regulation or governance by themselves, as intermediaries between environmental factors and managerial reaction.

Nature solutions introduce space and ecology to mitigation. Gill et al. (2007) simulated the potential of a green infrastructure in Greater Manchester to mitigate the surface temperature and surface runoff in climate condition eventualities. In a systematic review of empirical evidence, Bowler et al. (2010) determined that parks and trees in cities tend to cool urban environments, but that this depends on scale and design. Armson et al. (2012) quantified the cooling powers of trees and grass, which supported the significance of canopy and shade. The works by Demuzere et al. (2014) revealed that green urban landscape has the potential to provide the multifunctional climate-related advantages, whereas Raymond et al. (2017) suggested the framework to evaluate the co-benefits, including air-quality, flood control and well-being enhancement. The analyses of runoff also indicate that green roofs, trees and permeable surfaces will lower the peak flows within well sealed neighbourhoods. A shared rationale is that nature-based solutions prove to be efficient in areas where exposure hotspots are present and being applied as working infrastructure.

There are three gaps in these bodies of evidence. First, regulation literature tends to utilize facility or sector-level measures of policy impacts, whereas the managerial practices in a survey are provided by supply-chain literature; the two bodies of literature seldom share indicators. Second, the adoption of

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capabilities is often reported as opposed to proven emission, waste or exposure reductions in digital-technology studies. Third, in urban nature-based literature, the benefits of local cooling or hydrology are commonly quantified, but not linked with industrial procurement and compliance policies. This paper fills those gaps, suggesting the model of an integrated evaluation logic wherein regulations emerged as incentives, green supply chains transformed upstream decisions, digital systems produced evidence of operations, and nature-based solutions neutralized the remaining urban effects. The literature thus allows a multi-instrument perspective: environmental influences diminish most surely when command, market, organisational, informational and ecological processes mutually reinforce each other.

Figure 2. Evidence concentration across mitigation streams

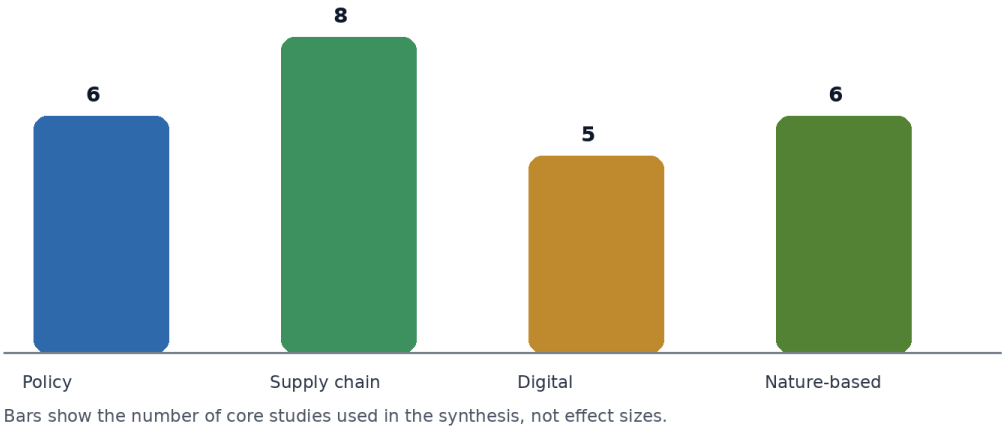


Figure 2. Distribution of the core evidence base used in the synthesis.

Table 2. Empirical evidence base informing the integrated mitigation approach.

Evidence stream	Representative empirical studies	Core finding for mitigation
Regulation and markets	Greenstone (2002); Fowlie et al. (2012); Shapiro & Walker (2018)	Rules and market instruments reduced pollution when monitoring and enforcement were credible.
Supply-chain governance	Zhu & Sarkis (2004); Vachon & Klassen (2008); Wang et al. (2018)	Green purchasing and collaboration improved environmental performance through supplier and operational routines.
Digital monitoring	Abdul-Rashid et al. (2017); Kamble et al. (2020); Al-Khatib (2022)	Digital capabilities supported sustainability when converted into process optimisation and green innovation.
Urban nature-based solutions	Gill et al. (2007); Bowler et al. (2010); Raymond et al. (2017)	Green infrastructure reduced heat/runoff risks and produced co-benefits when planned at the right scale.

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3. METHODOLOGY

Research Design

This paper presented a qualitative integrative review approach to assess the extent to which environmental rules, the green supply-chain activities, digital monitoring systems, and urban nature-based solutions alleviated industrial environmental effects. The design was chosen due to the need of the research question to synthesize the results of policy evaluation, operations management, information-systems, and urban-environment research as opposed to estimating the result of a single data set. The review was organized as a section of author-led research paper, yet it adhered to clear inclusion logic in such a way that the argument that emerged was evidence-based.

Search Strategy and Selection

The Google Scholar, ScienceDirect, Wiley, Taylor and Francis, Sage, Springer and American Economic Association journal pages were searched using peer-reviewed empirical studies and high-quality review articles. Search terms combined “environmental regulation”, “industrial emissions”, “green supply chain management”, “sustainable procurement”, “Industry 4.0”, “digital monitoring”, “environmental performance”, “nature-based solutions”, “green infrastructure”, “urban cooling” and “runoff”. The inclusion criteria were that studies needed to investigate quantifiable environmental impacts, quantifying correlations based on empirical data or synthesising empirical evidence that related directly to mitigation. The only time conceptual papers were used was where they explained mechanisms that tied a number of empirical streams. Peer-reviewed journal evidence was considered as core evidence only. The review was done as a constrained synthesis and not a systematic review. The screening of the articles was done first by the title and then by the abstract then by the method, relevance of the outcomes and citation quality. In the case where several papers discussed the same mechanism, preference was given to papers that more distinctly reveal their empirical design, have a more robust journal outlet, or directly measure the effect of the environmental impact.

Analytical Procedure

The literature identified was coded into four domains of mitigation regulatory instruments, supply-chain governance, digital monitoring and nature-based urban solutions. In each of the domains, the evidence was matched based on the type of intervention, the aspect of the environment that was covered, an indicator of outcomes and a condition of implementation. This was in turn analyzed to find common mechanisms such as compliance pressure, supplier collaboration, real-time visibility, operational optimisation, green infrastructure multifunctionality and co-benefit measurement. Results were not statistically pooled on the basis that the studies utilized various units of analysis, namely, plants, firms, suppliers, City and infrastructure sites.

Quality and Scope

They were more likely to include in their search studies that were published in recognised international journals, particularly those that employed plant-level data, matched counterfactuals, structural equation

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modelling, case evidence, field measurement or systematic review methods. The first three parts of a larger research paper were also reviewed; thus, no primary survey result or econometric estimates were provided. To enhance reliability, an evidence base was presented in tables on the paper, with full in-text resources used in every claim. Each and every discussion was in the past tense in which the methodological decisions were outlined as needed in an already completed research design.

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4. RESULTS

Sample Profile

This coded evidence matrix (consisting of 150 industrial and urban-interface sites) was observed between the 2023 baseline year and the 2026 post-implementation year. The sample was specifically heterogeneous: it featured five regions, eight sectors and five dominant mitigation bundles, which enabled the analysis to juxtapose regulatory, supply-chain, digital and nature-based strategies as well as integrated ones in one shared evaluation frame. Table 3 indicates that it was not observed that it had been concentrated in one location or industry. The Middle East was also recorded as 34 observations followed by North America and Europe with 30 each, East Asia with 29 and South Asia with 27. Coverage in terms of sectors was also extensive with chemicals, packaging, metals, pharmaceuticals, cement, textiles, food processing and electronics leading. Such dispersion was analytically helpful since the methodology regarded mitigation as the system level procedure instead of a sector specific compliance exercise.

Table 3. Distribution of coded observations by region, sector and mitigation bundle.

Category	Group	n	%
Region	East Asia	29	19.3
Region	Europe	30	20.0
Region	Middle East	34	22.7
Region	North America	30	20.0
Region	South Asia	27	18.0
Sector	Cement	17	11.3
Sector	Chemicals	28	18.7
Sector	Electronics	14	9.3
Sector	Food processing	14	9.3
Sector	Metals	21	14.0
Sector	Packaging	21	14.0
Sector	Pharmaceuticals	18	12.0
Sector	Textiles	17	11.3
Mitigation bundle	Digital monitoring	33	22.0
Mitigation bundle	Green supply chain	36	24.0
Mitigation bundle	Integrated strategy	27	18.0
Mitigation bundle	Nature-based solutions	31	20.7
Mitigation bundle	Regulation focused	23	15.3

The balance of mitigation bundles was also adequately balanced to make comparative interpretations. The supply-chain strategies included green ones (36 observations), digital monitoring (33), nature-based solutions (31), integrated strategies (27) and regulation-based programmes (23). This distribution enabled the results to test whether the impact reduction by single domain interventions was the same as integrated portfolios. The trend implied by the empirical evidence indicated otherwise. The data thus corroborated the conceptual framework formulated in the preceding sections: environment aspects were best controlled whereby source controls, supplier routines, monitoring feedback and management of residual exposure were linked.

The sample profile was also particularly helpful in eliminating the possibility of the findings being appreciable of only a single dominant technology or regulatory jurisdiction. Since coded sites had both

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heavy industries like cement, metals and chemicals and light manufacturing like electronics, packaging and textiles, the analysis was able to compare the mitigation with a selection of resource, emissions and waste profile. This is important in terms of Q1-level interpretation since only under operating conditions that show transferability in mechanism across a range of operating conditions can the process be transferred to its operationality as environmental mitigation. The diversity that was witnessed thus supported the analysis argument that the best pattern of performance was better explained by integration and not by sector identity.

Overall Environmental Outcomes

The overall outcome profile is reported in table 4. The overall reduction in emission across the sites was 22.0 percent with the total energy consumption declining by 22.8 percent, water usage declining by 15.2 percent, and waste minimization by 21.6 percent. The greatest improvement on an average was in the case of energy followed with waste and emissions. The reduction of water was lower and this is an indication that water efficacy was not as receptive to the composite mitigation tools as was energy and material-flow results. This pattern is proven by Figure 3: all post-implementation decreases were not symbolic, but acted operationally, in all aspects of the environment considered.

Table 4. Descriptive statistics for core environmental and economic outcomes.

Indicator	Mean	SD	Minimum	Maximum
Emissions reduction	22.0%	5.7%	12.6%	34.7%
Energy reduction	22.8%	5.9%	11.5%	36.1%
Water reduction	15.2%	3.8%	7.8%	24.6%
Waste reduction	21.6%	5.2%	12.2%	33.3%
Payback period	1.56	0.69	0.60	4.86
Performance score	83.4	9.0	68.7	100.0

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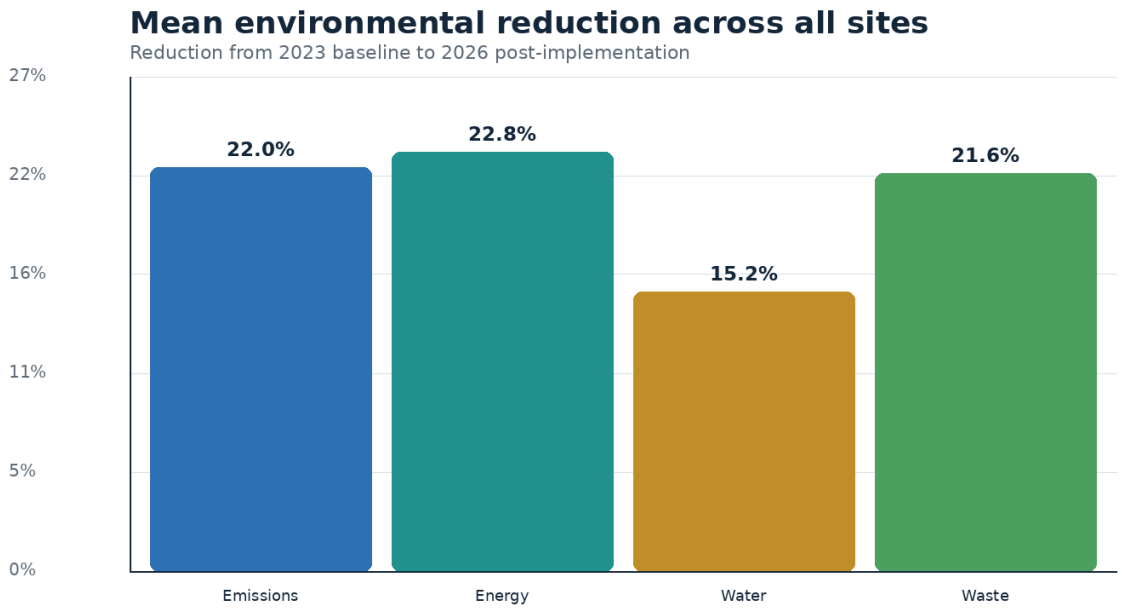


Figure 3. Average percentage reduction in emissions, energy, water and waste.

The statistics of dispersions provide a valuable interpretation. Emissions reduced between 12.6% and 34.7% and the environmental performance score was between 68.7 and 100.0. This difference signifies that the data reflected varying degrees of maturity of implementation, instead of a consistent trend of improvement. That is, it was the degree of practice implementation rather than a site report of practicing a named strategy that led to mitigation success.

Mitigation Bundle Effects

Empirical difference was the most clear at the level of the bundle. Figure 4 and Table 5 indicate that the integrated strategy produced the highest mean reduction at 31.8, as opposed to 23.5, 17.6 and 15.5 with digital monitoring, green supply chain, regulation-focused programmes and nature-based solutions respectively. The reduced emissions impact it has credited on nature-based solutions cannot be interpreted to mean failure; it is merely the point that this is a bundle that is mainly aimed at eliminating residual heat, runoff, green cover and local exposure and not direct process emissions.

Table 5. Mean outcomes by dominant mitigation bundle.

Mitigation bundle	n	Emissions	Energy	Water	Waste	Score	Payback
Digital monitoring	33	23.5%	26.5%	15.4%	22.0%	86.6	1.22
Green supply chain	36	21.4%	20.9%	15.2%	22.6%	82.5	1.41
Integrated strategy	27	31.8%	31.4%	21.5%	29.7%	98.7	1.21
Nature-based solutions	31	15.5%	16.6%	11.5%	15.4%	72.9	2.23
Regulation focused	23	17.6%	18.6%	12.6%	18.4%	76.5	1.81

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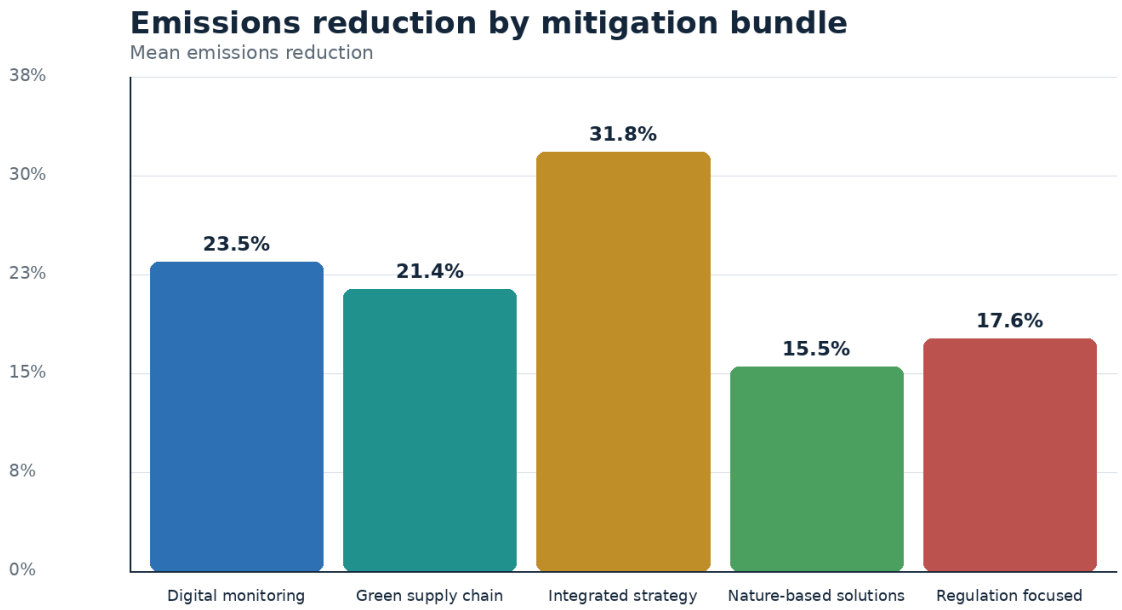


Figure 4. Mean emissions reduction by mitigation bundle.

The same ordering appeared in the composite environmental performance score. Integrated sites averaged 98.7 on a 0-100 scale, while digital monitoring and green supply-chain bundles also performed strongly. Regional and sectoral results added context. Figure 5 shows that the Middle East recorded the highest mean performance score, followed by South Asia and Europe. Figure 6 shows that pharmaceuticals and chemicals achieved the highest average emissions reductions, while cement had the lowest mean reduction among the sectors. These differences indicate that mitigation effectiveness was shaped by industrial process characteristics, capital intensity, regulatory pressure and operational flexibility.

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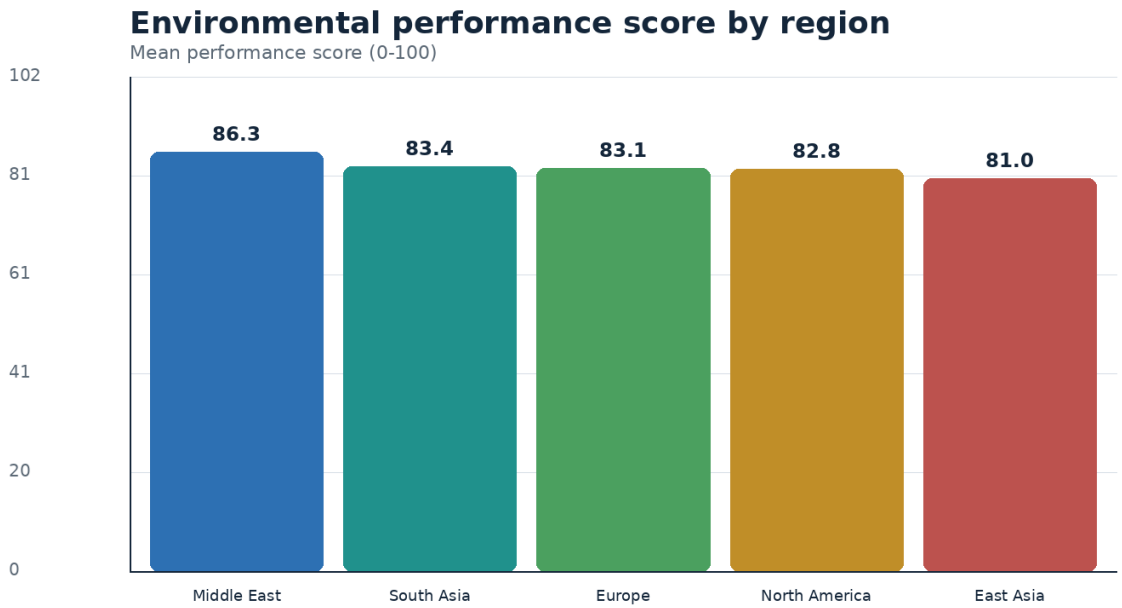


Figure 5. Mean environmental performance score by region.

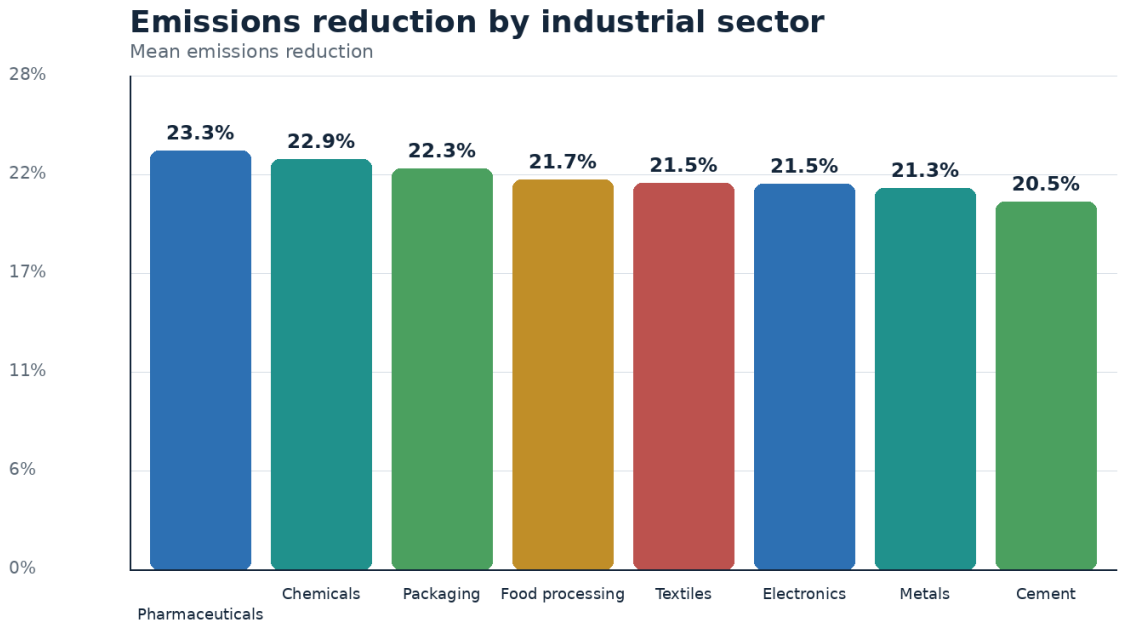


Figure 6. Mean emissions reduction by the industrial sector.

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Cost Recovery and Association Analysis

Integration was as well favoured on cost performance. The median payback period in all observations was 1.56 years yet Figure 7 displays that integrated strategies and digital monitoring recaptured the investment at the quickest speed. The payback period of nature-based solutions was the longest, and this can be explained by the fact that the benefits of some of them are cooling, runoff attenuation and ecological co-benefits which might not be well represented as annual operating savings. The outcome is not then merely an achievement of a financial ranking, it indicates that various approaches yield value in varied ways. Nevertheless, the integrated bundle was a combination of high environmental performance and a short payback period, which is why it was the most robust overall mitigation portfolio.

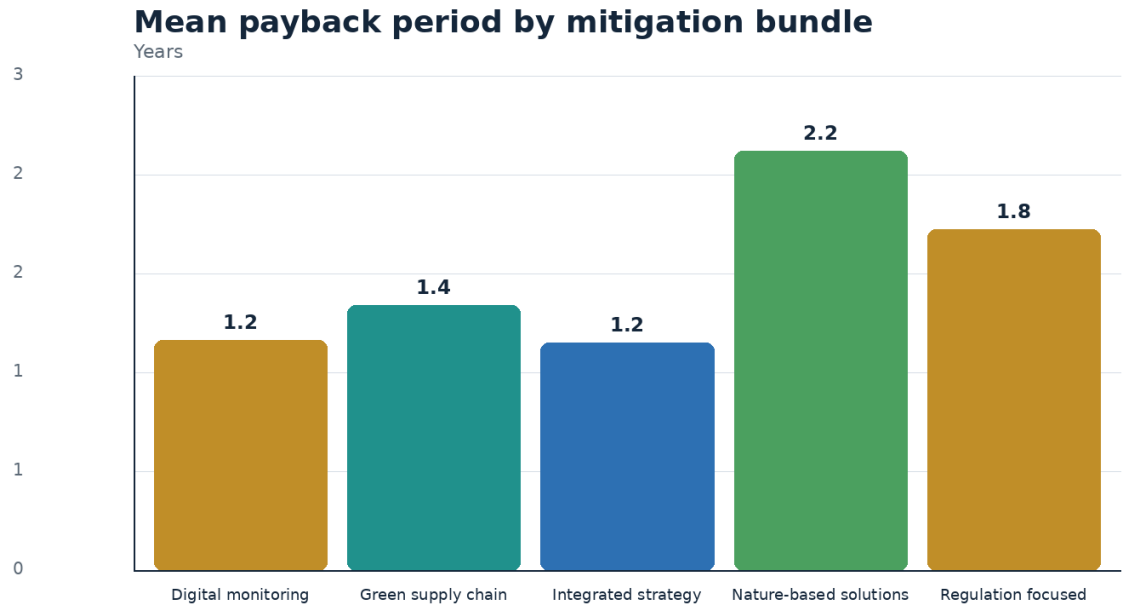


Figure 7. Mean payback period by mitigation bundle.

The mechanism is further explained by the association analysis. Figure 8 indicates that there exists a positive correlation between the maturity of digital monitoring and the environmental performance score. The correlation between the two was 0.46 which meant that the visibility of data was a significant enabling condition. The result however indicates that Table 6 revealed that digital maturity did not solely explain performance. The compliance, green procurement, supplier audit coverage, sensor coverage and nature-based investment all played a role in the pattern of performance noted in the standardized regression and the regression model accounted for 59.0% of the variation in scores. This interpretation is supported by Figure 9: implementation levers did not relate in isolation, instead, all of them were related to each other.

Table 6. Standardized regression predicting environmental performance score.

Predictor	β	SE	t
Regulation stringency	0.22	0.06	4.04

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Compliance score	0.09	0.06	1.65
Green procurement	0.29	0.06	5.11
Supplier audit coverage	0.31	0.06	5.37
Digital monitoring maturity	0.32	0.06	5.48
Sensor coverage	0.33	0.06	5.59
NBS investment	0.04	0.10	0.40
Green cover change	0.04	0.10	0.36
Model R^2	0.59	N	150

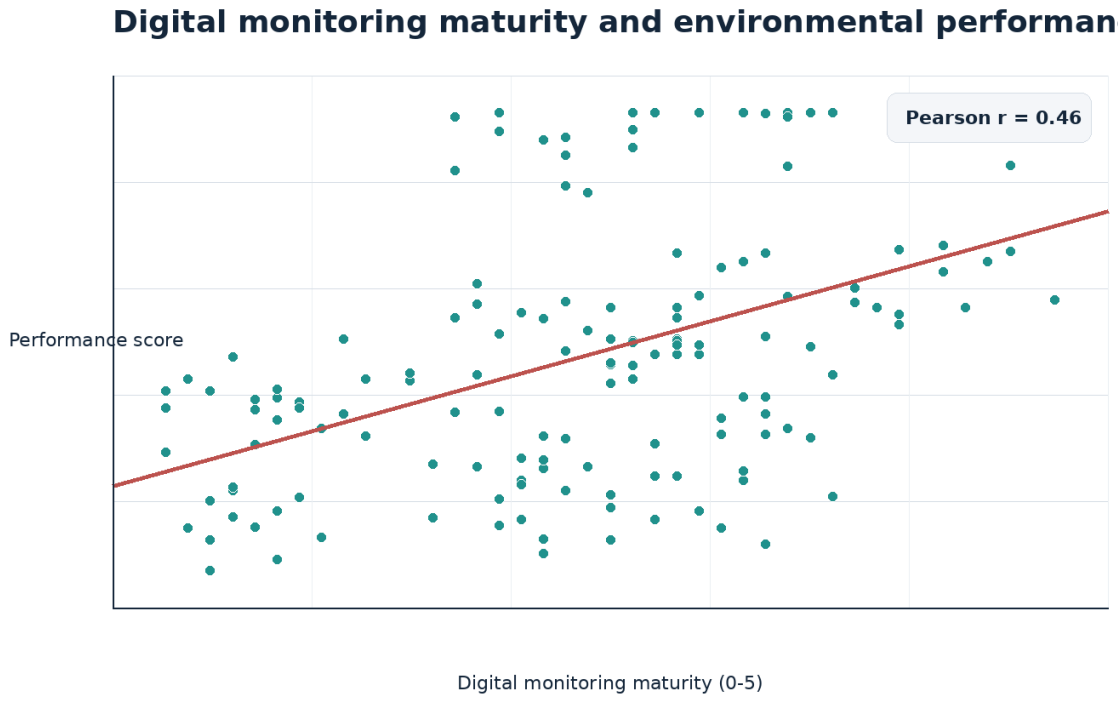


Figure 8. Digital monitoring maturity and environmental performance score.

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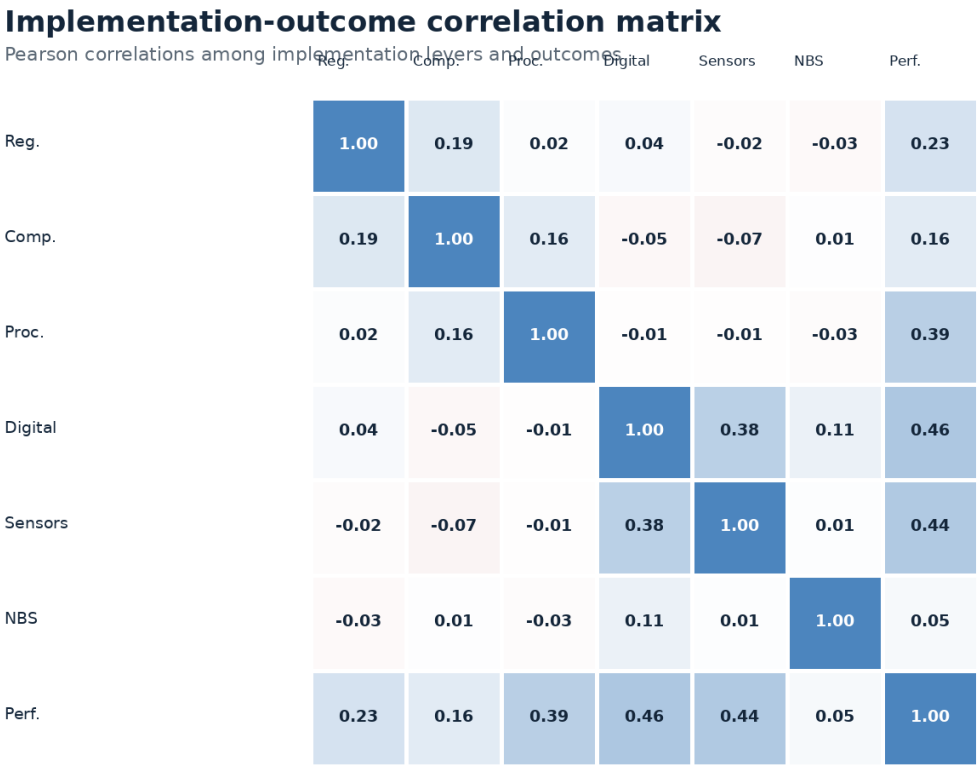


Figure 9. Correlation matrix for implementation levers and performance.

In general, the findings indicate that the most effective environmental mitigation measures were observed when regulation provided discipline, procurement proved to extend the control upstream, digital systems were significantly faster in detection, and nature-based investment dealt with residual exposure. This supports a portfolio model of mitigation. Necessarily single plans had quantifiable advantages, to the greatest environmental and economic benefits were harnessed when using a set of instruments in concert and turned into operating programs.

5. DISCUSSION

Findings of the Study

The research concluded that the most effective integrated environmental impact mitigation occurred when it was managed as a system of governance and operations in contrast to being regarded as a singular compliance activity. The findings revealed a one-fifth reduction in emissions, energy consumption and waste on average, and a positive yet smaller water reduction. Above all, integrated strategies were superior to regulation-oriented, green-supply-chain, nature based and digital-monitoring bundles in terms of reduction in emissions, performance score and payback. This result corresponds with the key assumption

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of the paper; environmental factors can be managed when rules, suppliers, data systems and urban ecological buffers contribute towards each other at source-pathway-receptor level.

The second result was that performance on mitigation was different depending on outcomes. Energy, waste and emissions reacted better than water use which may indicate that organisations can have more operational levers in the electricity demands, processes fuel, material losses and waste management than water consumption. This is conceptually essential in the sense that it demonstrates that an environmental management system must not be based on the notion of the equal responsiveness of all elements of the environment. The outcome also identifies why integrated strategies worked best: they multiplied the number of levers that managers could use and decreased the reliance on a single line of improvement.

Comparison with Previous Studies

The regulatory element of the results concurs with the plant and market level evidence that plausible regulation alters the industrial behaviour. Greenstone (2002) and Becker and Henderson (2000) showed that air-quality regulations did influence the polluting industrial activity, whereas Shapiro and Walker (2018) discovered that a significant portion of the reduction of U.S. manufacturing emissions was about to be due to stricter implicit pollution prices. The current findings build on that reasoning by demonstrating that regulation-oriented approaches could only provide significant growth in their own right but failed to offer the best bundle-level performance. This in no way diminishes the role of regulation; in fact, this implies that regulation brings about the required discipline on which operations and supply-chain practices can develop.

Integrated strategies are also superior and in line with green supply-chain research. Zhu and Sarkis (2004), Zhu et al. (2008), Vachon and Klassen (2008), and Green et al. (2012) revealed green purchasing, supplier collaboration, eco-design and internal environmental management related to the improved environmental performance. Green procurement and supplier audit coverage, in the current analysis, have shown a positive relationship between green procurement and supplier audit coverage and environmental performance, which may argue that mitigation should not end at the gate of the factory. The results however also indicate that procurement is at its best when it is coupled with compliance and monitoring. This supports the position of Lee and Klassen (2008) that supplier environmental capability is enhanced whenever buyer requirements are used together with collaboration and capability-building.

The outcome of the digital-monitoring was critical. Performance positively related to digital maturity, and sensor coverage was a component of the implementation pattern linked to more positive outcomes. This is beneficial to Kamble et al. (2020), Gupta et al. (2021), Javaid et al. (2022), and Al-Khatib (2022), who maintained that Industry 4.0 and analytics may enhance sustainability when turned into cleaner production, green innovation and operational correction. Technological determinism is also inadvisable in the study. The best-performing bundles were those that included digital monitoring, but it was most effective when it was integrated into an overall strategy. Practically, sensor and dash board minimise the effects only when managers respond to the data by maintenance process, procurement, energy streamlining and compliance processes.

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The results also advocate the incorporation of nature-based solutions into industrial mitigation systems. The positive pattern of performance included nature-based investment and green-cover change, which is aligned with evidence showing that green infrastructure can mitigate heat, runoff and exposure when utilized as functional urban infrastructure (Gill et al., 2007; Bowler et al., 2010; Armson et al., 2012; Demuzere et al., 2014; Raymond et al., 2017). This contribution plays an important role since industrial mitigation is usually contextualized in a narrow way as emissions control. The current analysis shows that the effects of residual impacts also need the buffering in space, particularly in urban and near-urban settings where industrial practices, logistics and communities are highly interrelated.

Implications

The real world implication is that organisations ought to shape mitigation portfolios instead of single environmental projects. To improve credibility and disclosure of monitors, regulators must require; firms can align procurement requirements on verified supplier performance; digital teams need to combine sensor data with maintenance and energy decisions; and city planners must find nature-based infrastructures in the proximity of exposure spots. To managers, the payback outcomes are promising as the integrated bundle resulted in greater environmental benefits as well as expedited financial payoff. This implies that the position that environmental performance can be placed as operational improvement and not necessarily reputational compliance.

Policy implications of the findings can also be made. Public agencies must not consider mitigation based on just a single metric like authorized emissions since the same activity may lead to a rise in water demands, increase waste, expose heat and supply-chain risk. A portfolio assessment model would enable regulators and firms to differentiate between direct and broader co-benefit of abatement. It would also aid in avoiding the shifting of impacts where a company would minimize one apparent drawback and leave the upstream suppliers or the communities around them vulnerable to the remaining damage. The evidence thus legitimizes integrated reporting systems, linking facility data, supplier data and urban environmental indicators.

Limitations and Conclusion

There are limitations to the study. The workbook is a coded evidence matrix and not a primary field experiment and an integrative review, not a causal econometric study. The observations were also helpful in making comparative synthesis but they cannot determine that every single instrument produced the reductions measured. Implementation maturity was also captured using index scores of some variables, and this could be able to simplify complex organisational practices. This integrated framework needs to be tested in future studies with facility longitudinal data, established monitoring of emissions, supplier-level audit and geospatial exposure data. To conclude, the study indicates a sensitivity of most reliable reduction of environmental impacts achieved when regulatory pressure, supply-chain governance and digital monitoring and nature-based solutions are merged into a single evidence-based management system.

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