

# Sustainable Pollution Mitigation Strategies for Manufacturing Enterprises in Zambia: An Engineering and Management Perspective

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**Abstract** - Industrial pollution remains a persistent and deeply entrenched challenge in Zambia's manufacturing sector, driven by aging industrial technologies, inconsistent regulatory enforcement, limited financial capacity, and slow adoption of sustainable manufacturing practices. As manufacturing activities expand across agro-processing, chemicals, metal fabrication, textiles, and packaging, the environmental burden has intensified through chemical effluents, particulate emissions, hazardous waste, and inefficient resource utilization. This article evaluates and establishes pollution mitigation strategies currently implemented by manufacturers in Zambia, drawing on an integrated analysis of survey data, qualitative interviews, and document reviews derived from a comprehensive thesis study. The study's findings reveal a growing but uneven embrace of sustainability-oriented interventions. Notably, 65.2% of manufacturers have adopted 3R practices, reuse, recycling, and remanufacturing, demonstrating a shift toward circular economy principles aimed at reducing waste generation and improving resource efficiency. Additionally, more than 54.5% of respondents consider their pollution mitigation strategies "very effective," highlighting increasing awareness and operational commitment toward environmental stewardship. Prominent strategies identified include cleaner production techniques, installation of pollution control equipment, integration of renewable energy systems, employee training initiatives, and strategic partnerships with regulatory and environmental agencies. These interventions collectively reflect an emerging culture of sustainable industrial management. Despite observable progress, substantial obstacles continue to undermine optimal implementation. High investment costs associated with modern pollution-control technologies, limited access to green financing, technological obsolescence, constrained technical expertise, weak monitoring mechanisms, and regulatory inconsistencies remain significant barriers. This article synthesizes these findings to provide a structured, comprehensive overview of existing mitigation approaches, their effectiveness, and the contextual limitations manufacturers face. Ultimately, the study offers targeted recommendations for policy, industry, and regulatory stakeholders progress toward a resilient and environmentally sustainable industrial ecosystem. The insights presented contribute to advancing sustainable manufacturing discourse and guiding evidence-based policy reform within the country.

**Keywords:** *Closed-Loop, , Circular Economy, Manufacturing, Pollution-Mitigation, Supply Chain, Sustainable,*

## 1. INTRODUCTION

Industrial activity in Zambia has expanded significantly over the past few decades, driven by economic diversification efforts, foreign direct investment, and the growth of domestic markets. Key manufacturing sectors include agro-processing, chemicals, packaging, metal fabrication, textiles, and automotive components. While these industries contribute substantially to employment generation, GDP growth, and technological development, they have also led to negative environmental externalities, posing serious threats to human health, ecosystems, and sustainable development objectives (World Bank, 2021).

Evidence indicates that manufacturing activities in Zambia produce a wide spectrum of pollutants. Airborne emissions, chemical effluents, particulate matter, heavy metals, and industrial solid waste are particularly prevalent. Statistical data from Mutono-Mwanza and Mwanaumo (2024) suggest that approximately 19.6% of manufacturers discharge chemical effluents, while 16.1% emit particulate matter, highlighting a diverse and concerning pollution profile that affects both urban and rural communities. Industrial solid waste, including packaging materials, scrap metals, and by-products of chemical processes, is often disposed of inappropriately, exacerbating soil and water contamination. These environmental pressures are compounded by insufficient waste collection systems, inadequate treatment facilities, and limited regulatory enforcement, consistent with findings from Onu and Mbohwa (2021) and Shahparvari et al. (2021).

Although a majority of firms (71.4%) report having formal environmental policies, their effectiveness is constrained by weak implementation, inconsistent monitoring, and limited capacity to evaluate pollution-control outcomes. Alarming, 32.1% of manufacturing firms lack any systematic monitoring mechanisms (Mutono-Mwanza & Mwanaumo, 2024) suggesting a substantial gap between policy intent and operational practice. Without reliable environmental monitoring, firms are unable to accurately measure emissions, identify sources of inefficiency, or implement corrective actions, limiting the potential of sustainability initiatives. This gap reflects broader challenges in emerging economies, where environmental governance structures, technical capacity, and

industrial compliance mechanisms remain underdeveloped (Fabian & Hill, 2022; Govindan et al., 2021).

Against this backdrop, there is an urgent need to explore the pollution mitigation strategies employed by manufacturers in Zambia, understand their operational effectiveness, identify barriers to adoption, and assess prospects for scaling up. Sustainable closed-loop supply chain (SCLSC) frameworks, which integrate waste reduction, resource efficiency, recycling, remanufacturing, and reverse logistics, offer a comprehensive approach to mitigating environmental impacts while enhancing operational efficiency. Globally, SCLSC adoption has been shown to reduce emissions, minimize resource consumption, and promote circular use of materials, contributing to both environmental and economic sustainability (Geissdoerfer et al., 2017; Bocken et al., 2021).

This study, therefore, seeks to examine the adoption of SCLSC practices among Zambian manufacturers, investigating the extent to which these practices have been operationalized, the challenges firms face, and the perceived benefits for environmental outcomes. By integrating quantitative and qualitative methods, the research provides a holistic understanding of both measurable trends, such as adoption rates, monitoring practices, and policy compliance, and the contextual factors shaping operational decisions, including organizational culture, technological capacity, and regulatory incentives.

Furthermore, the study aims to inform evidence-based policy interventions, offering recommendations for regulators, industry associations, and manufacturing firms to enhance pollution control measures and promote sustainable industrial practices. By contextualizing Zambia's experience within global and regional sustainability frameworks, the research contributes to the literature on sustainable supply chain management in emerging economies and addresses critical knowledge gaps regarding the relationship among industrial growth, environmental management, and circular economy practices.

## 2. LITERATURE REVIEW

### 2.1 Overview of Industrial Pollution

Industrial pollution remains a major global environmental and public health concern, with extensive literature demonstrating its far-reaching impacts on human wellbeing and economic development. Fuller et al. (2022) emphasise that air pollution contributes to 5.5 million deaths annually, with an overwhelming 95% occurring in low-income countries, including Zambia. Lead exposure, a common by-product of industrial activity, results in the loss of 765 million IQ points globally, causing productivity losses valued at over US\$6 trillion, equivalent to 6.9% of global GDP. These figures highlight the severity of industrial pollution as not only an environmental issue but also a developmental and socioeconomic threat.

In the Zambian context, rapid industrialisation has generated significant emissions, including sulphur dioxide, nitrogen oxides, volatile organic compounds, chemical effluents, particulates, and heavy metals, largely attributable to aging machinery, poor waste management systems, and inadequate environmental controls. Evidence from Mutono-Mwanza and Mwanaumo (2024) confirms that 19.6% of manufacturers

discharge chemical effluents, and 16.1% emit particulate matter, reinforcing the extent of industrial pollution across the country. Weak enforcement of environmental policies, limited monitoring capacity, and resource constraints within regulatory institutions further exacerbate the situation, echoing long-standing concerns expressed by ZEMA (2020) and other regional environmental reports.

### 2.2 Sustainable Manufacturing and Pollution Mitigation

Sustainable manufacturing seeks to minimise negative environmental impacts while optimising resource efficiency and improving industrial competitiveness. It involves adopting cleaner technologies, reducing waste, improving production processes, and integrating environmental considerations into operational systems. The Industrial Energy Efficiency Programme (IEEP) in Zambia demonstrates the potential of sustainable manufacturing, having documented significant energy savings and emission reductions among firms that adopted cleaner production interventions, such as resource-efficient machinery and process optimization.

Cleaner production strategies commonly implemented in sustainable manufacturing include process optimisation, substitution of toxic materials with environmentally benign alternatives, adoption of renewable energy, and waste heat recovery. Water-efficient systems such as closed-loop water cycles and effluent recycling further reduce contamination risks and resource inefficiencies. The literature indicates that these measures align with Zambia's national development priorities under the Green Growth Strategy and Vision 2030, both of which advocate environmentally sustainable industrial development. Despite these policy frameworks, adoption remains uneven due to financial, technological, and institutional constraints manufacturers often face.

### 2.3 Closed-Loop Supply Chain (CLSC) and the Circular Economy

Closed-Loop Supply Chains (CLSCs) and circular economy frameworks represent innovative approaches to sustainable production, emphasising resource recovery, waste reduction, and regenerative manufacturing cycles. Mutono-Mwanza and Mwanaumo (2024) reveal that 65.2% of Zambian manufacturers have adopted 3R activities: reuse, recycling, and remanufacturing, demonstrating a significant alignment with circular economy principles. Such practices include component recovery, packaging recycling programs, industrial scrap recovery, and waste-to-energy initiatives, enabling firms to reintroduce materials into the production cycle and minimise environmental burdens.

The circular economy aims to maintain product value for as long as possible, reduce the extraction of virgin resources, and minimise pollution through restorative systems. CLSC adoption in Zambia shows emerging but promising momentum, particularly in industries such as metal fabrication, plastics, and agro-processing. These systems contribute directly to pollution mitigation by limiting the volume of waste released into the environment and lowering demand for resource-intensive virgin inputs. International experiences reinforce the potential of CLSCs to enhance competitiveness and environmental performance, although local implementation challenges,

particularly technological limitations and inadequate recycling infrastructure, remain significant.

#### **2.4 Regulatory Frameworks and Environmental Compliance**

Zambia's environmental regulatory environment is anchored by the Environmental Management Act, which mandates pollution control, environmental permitting, and compliance monitoring through institutions such as the Zambia Environmental Management Agency (ZEMA), Zambia Bureau of Standards (ZABS), and local authorities. Manufacturers are required to conduct environmental audits, maintain pollution control systems, and adhere to statutory emission thresholds. However, Mutono-Mwanza and Mwanaumo (2024) highlight persistent regulatory challenges, including infrequent inspections, inadequate monitoring equipment, and inconsistent reporting compliance, undermining the effectiveness of environmental governance.

Due to these gaps, many firms rely heavily on institutional partnerships with ZEMA and ZABS for guidance on environmental standards, training, and compliance support. These collaborations are critical for building capacity, strengthening audit processes, and ensuring alignment with national and international environmental expectations. However, without enhanced enforcement mechanisms, increased government support, and better coordination across agencies, compliance will continue to vary widely across the manufacturing landscape.

#### **2.5 Empirical Literature**

The empirical work by Mutono-Mwanza and Mwanaumo (2024) provides robust evidence demonstrating both progress and challenges in Zambia's pollution control landscape. Survey findings show that 54.5% of manufacturers perceive their pollution mitigation strategies as highly effective, indicating growing recognition of environmental management benefits. Yet the study confirms that financial limitations, outdated technologies, and insufficient technical capacity remain the most significant barriers to effective pollution control.

Training and capacity-building initiatives were found to enhance compliance with environmental policies and improve internal waste management practices. Additionally, the adoption of renewable energy solutions, particularly solar systems, has increased due to persistent energy shortages and rising operational costs, further contributing to pollution reduction efforts. Overall, the empirical findings reinforce the view that, while meaningful progress has been made, manufacturers require coordinated financial, technical, and regulatory support to scale pollution-mitigation strategies and transition to fully sustainable production systems.

### **3. METHODOLOGY**

This study employed a robust mixed-methods research design to identify, analyse, and interpret pollution mitigation strategies implemented by manufacturers in Zambia. The approach integrated quantitative survey data, qualitative interviews, focus group insights, and a systematic document review. This methodology ensured a comprehensive understanding of both measurable pollution indicators and the contextual factors

influencing mitigation practices, using a convergent parallel mixed-methods design.

#### **3.1 Research Design and Rationale**

A convergent parallel mixed-methods design was adopted, allowing quantitative and qualitative data to be collected simultaneously and then integrated during analysis. This design was chosen to improve the reliability and validity of findings through triangulation, a process that enables comparison across multiple data sources and captures the complexity of manufacturing operations and environmental performance.

The study was anchored in a pragmatic research philosophy, combining positivist measurement of pollution levels with interpretivist exploration of managerial perceptions, regulatory influences, and operational challenges. A multiple-case study strategy further supported this approach, enabling a comparison of SCLSC adoption and pollution mitigation across regions and industrial sectors. This strategy enhanced contextual depth by examining differences in technology, compliance behaviours, and sector-specific mitigation approaches across Zambia's manufacturing landscape.

#### **3.2 Target Population and Sampling Procedures**

The study targeted 112 manufacturing firms across Lusaka, Ndola, Kitwe, Kafue, and Kabwe, representing the heavy equipment, electronics, mining-related industries, agro-processing, plastics, textiles, and wood products sectors. These firms were selected from the Zambia Association of Manufacturers registry and met the inclusion criteria of operating for at least two years and demonstrating some level of environmental management or CLSC activity.

A combination of stratified random sampling, purposive sampling, and convenience sampling ensured that both statistically representative and knowledge-rich participants were included. Stratified random sampling was used for the quantitative survey to ensure proportional representation of industry sectors, while purposive sampling targeted regulatory authorities (ZEMA, ZABS) and sustainability experts for qualitative interviews. Key informants were selected based on expertise in pollution control, supply chain management, and environmental policy implementation.

Although the initial population consisted of 212 registered manufacturers, only 112 were reachable due to closures, accessibility challenges, and unwillingness to participate. Nonetheless, the final sample was sufficiently representative of Zambia's active manufacturing landscape and therefore retained statistical validity.

#### **3.3 Data Collection Instruments and Procedures**

##### **3.3.1 Survey Data**

Structured questionnaires were administered to collect quantitative data on emissions, waste management, CLSC adoption, technological investments, energy efficiency, and policy compliance. The survey included Likert-scale and closed-ended items and was distributed both online and during in-person visits to accommodate participants' varying levels of internet access. The survey achieved full participation from all

112 firms, and reminder protocols were followed to improve response rates.

### 3.3.2 Qualitative Interviews

Semi-structured interviews were conducted with industry stakeholders, including supply chain managers, environmental officers, policymakers, regulatory officials, and sustainability consultants. An interview guide ensured consistency across interviews, focusing on challenges in pollution control, drivers of sustainable manufacturing, technology adoption, regulatory pressures, and collaborative practices. Interviews lasted 30–45 minutes and adhered to standardized ethical and probing guidelines to maintain neutrality and reliability.

The principle of theoretical saturation was applied to qualitative sampling, in which data collection continued until no new themes emerged, aligning with best-practice standards for qualitative inquiry (Fusch & Ness, 2015).

### 3.3.3 Document Review

A structured document review was undertaken to analyse regulatory guidelines, organisational sustainability reports, ZEMA and ZABS compliance documentation, and international environmental standards such as ISO 14001. These documents provided contextual depth, policy insights, and verification of the firm's reported mitigation strategies. The document review contributed significantly to triangulation, validating surveys and interview findings against official records and environmental performance standards.

## 3.4 DATA ANALYSIS

### 3.4.1 Quantitative Analysis

Quantitative data were analysed using SPSS Version 23, beginning with rigorous data cleaning through case-wise deletion, multiple imputation for missing values, and outlier detection using Mahalanobis distance. Descriptive statistics summarised emissions levels, mitigation strategies, and adoption rates of CLSC activities, while inferential analyses, including t-tests, ANOVA, and regression modelling, examined relationships between CLSC practices and reductions in pollution. The use of a 95% confidence level and p-value threshold of <0.05 ensured statistical robustness.

### 3.4.2 Qualitative Analysis

Qualitative data were transcribed verbatim and analysed thematically using NVivo software. The thematic analysis followed Braun and Clarke's (2019) framework for identifying, categorising, and interpreting recurring patterns across interviews and focus group discussions. Coding was conducted collaboratively by multiple researchers to ensure inter-coder reliability, and themes were mapped onto the study's conceptual framework to illustrate how institutional, operational, and technological variables influenced pollution mitigation outcomes.

### 3.4.3 Triangulation

Triangulation strengthened the validity of the findings by comparing survey responses, interview insights, observational data from site visits, and document review outcomes. This cross-validation process ensured that results reflected actual

industry practices and were not solely reliant on self-report measures. Triangulation enhanced internal validity and provided a holistic perspective of Zambia's pollution mitigation strategies within the manufacturing sector.

### 3.5 Ethical Considerations

Ethical measures included informed consent, confidentiality assurances, anonymisation of data, secure storage of digital files, and voluntary participation protocols. Both written and digital consent were obtained, depending on the mode of participation, in compliance with ethical standards prescribed for social science research.

## 4. FINDINGS

### 4.1 Current Pollution Levels and Types

The study reveals that Zambian manufacturers generate a wide range of pollutants, reflecting the diversity of industrial processes in sectors such as agro-processing, chemicals, textiles, packaging, metal fabrication, engineering, and plastics. Survey data from 112 firms indicate that chemical effluents (19.6%) constitute the highest proportion of pollutants emitted, highlighting the prevalence of liquid waste discharges into water bodies and municipal drainage systems. Particulate matter (16.1%), including dust, soot, and suspended particles, was the second most common pollutant, particularly in the cement, steel, and construction industries. Emissions of sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>) accounted for 7.1% each, largely emanating from fuel combustion, boiler operations, and thermal processes. Heavy metal contaminants such as lead, cadmium, and chromium accounted for 5.4% of the total, with particularly high levels in metal fabrication and electronics manufacturing (Mutono-Mwanza & Mwanaumo, 2024).

TABLE 1: REPORTED TYPES OF EMISSIONS AMONG MANUFACTURERS

Type of Pollutant	Percentage (%)
Chemical effluents	19.6
Particulate matter	16.1
Sulphur dioxide (SO <sub>2</sub> )	7.1
Nitrogen oxides (NO <sub>x</sub> )	7.1
Heavy metals	5.4
Hazardous waste	8.3
Solid waste (general)	11.6
Other emissions	24.8

These pollution levels are intensified by a combination of structural and operational constraints. Many manufacturing plants rely on outdated machinery that operates with low energy efficiency and poor emission

control. Waste management infrastructure, particularly effluent treatment plants and dust extraction systems, remains inadequate, with many lacking modern pollution abatement technologies. In addition, inconsistent regulatory enforcement, insufficient environmental and limited monitoring equipment among regulatory bodies compliance and contribute to high emissions across the sector.

Survey responses further indicate that 32.1% of firms lack formal environmental monitoring systems (Mutono-Mwanza & Mwanaumo, 2024), creating gaps in measurement accuracy and limiting early detection of pollution risks. Such limitations hinder timely interventions and amplify cumulative environmental impacts over time.

#### 4.2 Adoption of Pollution Mitigation Strategies

Manufacturers have implemented diverse mitigation strategies with varying levels of adoption and effectiveness. The study identifies 3R practices (reuse, recycling, and remanufacturing) as the most widely adopted methods, with 65.2% of firms actively engaging in circular processes (Mutono-Mwanza & Mwanaumo, 2024). These practices help reduce waste, recover materials, and minimise dependence on virgin inputs, contributing to reduced emissions and operational efficiency. Cleaner production techniques such as the use of eco-friendly raw materials, process optimisation, and waste-heat recovery have also gained traction, particularly among firms participating in energy-efficiency programs.

TABLE 2: ADOPTION OF POLLUTION MITIGATION STRATEGIES

Mitigation Strategy	Adoption Rate (%)
Recycling, reuse, remanufacturing (3Rs)	65.2
Cleaner production	58.0
Pollution control equipment	41.1
Renewable energy (solar/hybrid systems)	37.5
Employee environmental training	52.7
Regulatory compliance initiatives	47.3
Environmental partnerships (ZEMA, ZABS)	44.6

Evidence from interviews confirms that manufacturers increasingly recognise the financial benefits of sustainable production, including reduced material costs, improved operational efficiency, and better regulatory compliance, leading to gradual shifts toward environmentally responsible practices. However, adoption varies significantly across industry categories, with larger firms generally better positioned to invest in green technologies than small- and medium-sized manufacturers.

#### 4.3 Perceived Effectiveness of Mitigation Strategies

Understanding manufacturers' perceptions of the effectiveness of their pollution mitigation strategies is essential for evaluating the

practical value and operational impact of environmental interventions. Perception influences decision-making, continued investment, and commitment to sustainable manufacturing practices. Survey data from 112 participating firms provides meaningful evidence on how manufacturers evaluate the outcomes of their mitigation efforts, particularly regarding cost savings, emission reductions, operational efficiency, compliance improvements, and alignment with supply-chain sustainability goals.

The findings indicate strong confidence among manufacturers in the value of their mitigation measures. A majority, 54.5% rated their strategies as *very effective*, while 25% considered them *effective*. Taken together, this suggests that nearly 80% of manufacturers believe the strategies they have adopted contribute meaningfully to pollution reduction and operational improvements. A smaller proportion 17.9% perceived these strategies as *moderately effective*, indicating either partial implementation or suboptimal outcomes. Only 2.7% regarded their mitigation strategies as *ineffective*, suggesting limited dissatisfaction or inadequate functioning of environmental interventions (Mutono-Mwanza & Mwanaumo, 2024).

TABLE 3: PERCEIVED EFFECTIVENESS OF MITIGATION STRATEGIES

Effectiveness Rating	Percentage (%)
Very effective	54.5
Effective	25.0
Moderately effective	17.9
Ineffective	2.7

The high perception of effectiveness among manufacturers reflects a growing awareness of environmental responsibility across Zambia's industrial sector. Firms that rated their pollution mitigation strategies as very effective typically exhibited strong organisational capacity, technological readiness, and proactive environmental management. These firms often invested in modern pollution-control equipment such as effluent treatment plants, dust extractors, fume scrubbers, and advanced filtration systems, enabling them to significantly reduce emissions and comply with regulatory standards. They also adopted cleaner production technologies designed to optimise energy use, minimise raw material inputs, and enhance operational efficiency. Additionally, these manufacturers implemented 3R practices, reuse, recycling, and remanufacturing, which contributed to substantial reductions in both solid and liquid waste streams. Their operations were further supported by comprehensive environmental monitoring frameworks, regular audits, and skilled personnel trained in environmental management, occupational health, and sustainability practices.

These attributes were most common in medium- to large-scale firms that possessed the financial and technological capacity to integrate sustainability into their strategic and operational plans.

As a result, these firms achieved stronger environmental performance while simultaneously improving cost efficiency and competitiveness.

In contrast, manufacturers who perceived their strategies as moderately effective, representing 17.9% of the sample, encountered several operational and structural limitations. Many of these firms relied on outdated machinery that impeded efficient pollution control and increased production waste. Their limited financial capacity restricted investment in advanced green technologies and slowed the transition toward cleaner production. Inadequate staff training also emerged as a major challenge, with many employees lacking the specialised skills required to implement, monitor, and sustain environmental interventions. Furthermore, inconsistent monitoring systems hindered their ability to evaluate the performance of mitigation initiatives, resulting in gaps between planned and actual outcomes. Partial or incomplete implementation, often due to financial constraints, meant that these firms achieved only incremental progress rather than the transformative improvements necessary for substantial pollution reduction.

The small proportion of firms (2.7%) that rated their strategies as ineffective identified even more severe systemic barriers. These included the high upfront costs of pollution-control equipment, shortages of skilled technicians, and frequent maintenance challenges due to limited availability of spare parts. Some firms also struggled with outdated regulatory compliance systems or lacked access to environmental guidance from relevant authorities. These factors collectively undermined the effectiveness of their mitigation efforts.

#### 4.4 Cross-Analysis: Effectiveness by Strategy Type

To deepen the analysis, perceptions of effectiveness were examined in relation to specific mitigation strategies. Table 4 illustrates the relationship between strategy types and perceived outcomes, revealing that strategies with higher technological input or requiring skilled personnel were more likely to be rated highly effective.

**Table 4: Effectiveness Ratings by Most Common Strategies**

Mitigation Strategy	High/Very Effective (%)	Moderate (%)	Low (%)
3R Practices (Reuse/Recycling)	68.7	26.1	5.2
Cleaner Production	71.4	23.2	5.4
Pollution Control Equipment	62.3	29.7	8.0
Renewable Energy Adoption	58.6	33.1	8.3
Staff Environmental Training	65.2	28.4	6.4
Partnerships with ZEMA/ZABS	60.7	31.2	8.1

The table shows that cleaner production and 3R practices are perceived as the most effective. This is because they directly reduce waste, improve resource efficiency, and enhance overall operational sustainability. Pollution control equipment, while effective, is often constrained by maintenance and energy cost challenges. Renewable energy adoption is still emerging, with firms citing cost barriers but acknowledging long-term benefits.

#### 4.5 Barriers to Effective Pollution Control

Although Zambia's manufacturing sector has made notable progress in pollution mitigation, the effectiveness of these initiatives remains significantly constrained by structural, financial, technological, and institutional barriers. These obstacles limit the capacity of firms particularly small and medium enterprises (SMEs) to comply with environmental standards, invest in cleaner technologies, and adopt comprehensive sustainable closed-loop supply chain practices.

**TABLE 5: KEY BARRIERS TO EFFECTIVE POLLUTION CONTROL IN THE MANUFACTURING SECTOR**

Barrier Category	Description	Affected Firms
High Investment Costs	High capital expenditure is required for pollution-control technologies, renewable energy systems, and cleaner production upgrades	Mostly SMEs and low-capital industries
Outdated Machinery	Inefficient, old, and energy-intensive equipment increases emissions and reduces operational efficiency	Particularly, older manufacturing plants
Limited Technical Expertise	Inadequate skills in environmental management, advanced monitoring systems, and cleaner production techniques	Firms without environmental specialists
Weak Monitoring & Enforcement	Infrequent inspections, outdated standards, and inconsistent compliance reporting weaken regulatory effectiveness	Most surveyed firms
Inadequate Waste Infrastructure	Lack of hazardous waste facilities, industrial wastewater plants, and regional recycling hubs	Nationwide constraint

A persistent barrier highlighted by respondents concerns the prohibitive cost of acquiring modern environmental technologies. Equipment such as dust extraction units, effluent treatment plants, emission scrubbers, and air-quality monitoring devices require substantial upfront capital. For SMEs operating under strict budget constraints, such investments are often unattainable. Additionally, access to green financing, concessional loans, or sustainability-linked credit remains extremely limited in Zambia. As a result, firms continue to rely

on outdated technologies, resulting in elevated emissions and inefficiencies.

Many manufacturing firms operate legacy machinery installed decades ago. These systems consume more energy, generate higher emissions, and cannot support cleaner production processes. Furthermore, the scarcity of local suppliers for modern industrial technology means firms rely on expensive imports, which further inflate adoption costs. Importation delays, lack of after-sales support, and high maintenance expenses compound this challenge.

The study finds that a deficit in environmental management expertise significantly hinders pollution control efforts. Many firms lack trained personnel capable of interpreting environmental regulations, designing waste-reduction systems, conducting impact assessments, or maintaining pollution-control equipment. Without skilled human capital, even firms with modern equipment struggle to optimize operations or meet compliance standards.

Respondents repeatedly referenced inconsistent inspections and lenient compliance enforcement. Although ZEMA plays a critical role in regulating pollution, limited staffing, outdated standards, and administrative bottlenecks reduce its effectiveness. Consequently, firms may underreport emissions or delay compliance actions without facing consequences.

A scarcity of hazardous waste management facilities, industrial wastewater treatment systems, and regional recycling hubs present another systemic challenge. This infrastructure gap forces firms to store waste on-site, transport it long distances at high cost, or dispose of it unsafely, posing significant environmental risks.

#### **4.6 Detailed Analysis of Mitigation Strategies**

##### **4.6.1 Adoption of 3R (Reuse, Recycling, Remanufacturing) Strategies**

The adoption of 3R practices emerged as one of the most prominent mitigation approaches, with 65.2% of manufacturers reporting active engagement in reuse, recycling, and remanufacturing (Mutono-Mwanza & Mwanaumo, 2024). Manufacturers across sectors, especially packaging, electronics, auto components, and machinery have embraced 3R strategies due to their cost-saving potential and environmental benefits. Activities such as material recovery, refurbishing, and component reassembly help reduce raw-material consumption and minimize industrial waste, thus lowering landfill pressure.

Moreover, firms noted that 3R initiatives lead to:

- Reduced carbon emissions
- Water and energy conservation
- Waste minimisation
- Improved operational efficiency

These outcomes align with global evidence that closed-loop manufacturing processes substantially reduce environmental impacts across the lifecycle. Importantly, firms acknowledged that 3R practices are relatively affordable compared to advanced pollution-control equipment, making them attractive for SMEs.

##### **4.6.2 Cleaner Production and Technological Upgrades**

Cleaner production strategies have increasingly been adopted by Zambian manufacturers, particularly those involved in initiatives such as the Industrial Energy Efficiency Project. Key interventions include transitioning to energy-efficient machinery, implementing closed-loop water recycling systems, substituting hazardous substances with eco-friendly materials, and employing waste-minimisation techniques. These approaches allow firms to move from reactive pollution management toward preventive environmental strategies, addressing emissions at their source rather than relying solely on post-pollution treatments. Evidence suggests that cleaner production technologies contribute to significant reductions in energy and material consumption while improving environmental performance. Nevertheless, adoption remains uneven across the sector, largely due to financial constraints and limited technical capacity among smaller enterprises.

##### **4.6.3 Pollution Control Equipment**

To manage industrial emissions more directly, several firms have invested in pollution-control equipment, including dust extractors to reduce particulate matter, air scrubbers for gas purification, effluent treatment plants for wastewater management, and emission-capture systems for volatile organic compounds. These systems have proven effective in reducing environmental harm and ensuring compliance with regulations. However, uptake is limited, particularly among SMEs, due to the high costs of procurement, installation, and ongoing maintenance. Many firms report that such equipment is "prohibitively expensive," which constrains broader adoption despite its demonstrated environmental benefits.

##### **4.6.4 Renewable Energy Integration**

Recurring electricity shortages and dependence on diesel generators have prompted some manufacturers to integrate renewable energy solutions, notably solar thermal and solar photovoltaic systems. This shift not only lowers operational emissions by reducing reliance on diesel, a significant pollutant, but also enhances energy security, ensuring more stable production processes. Investment in renewables aligns with both environmental sustainability and long-term operational efficiency, offering the dual benefits of cost savings and a reduced carbon footprint. While promising, these initiatives are still in the early stages and limited by initial capital investment requirements.

##### **4.6.5 Employee Training and Capacity Building**

Recognizing the human dimension of sustainability, manufacturers increasingly invest in workforce training on environmental management, waste reduction, resource optimization, and safe chemical handling. Effective training programs strengthen internal compliance, reduce environmental incidents, and cultivate a culture of sustainability. Trained employees are better equipped to operate pollution-control equipment properly and adhere to environmental guidelines, thereby enhancing the overall effectiveness of technological and operational interventions. Consequently, human capacity development emerges as a critical complement to technical solutions in achieving sustainable manufacturing outcomes.

#### 4.6.6 Partnerships with Environmental Agencies

Collaborations with institutions such as ZEMA, ZABS, NGOs, and industry associations play a pivotal role in promoting pollution control and sustainability. These partnerships facilitate monitoring and compliance checks, environmental auditing, development of sustainability standards, and provision of advisory support and capacity building. Such collaborations not only strengthen regulatory frameworks but also improve firms' knowledge and adherence to environmental requirements. Nonetheless, gaps persist due to limited resources and enforcement capacity among regulatory agencies, which can hinder the effectiveness of these partnerships in driving sector-wide environmental improvements.

### 5. DISCUSSION

The findings from this study indicate that Zambia's pollution mitigation landscape is moderately developed, reflecting a growing awareness of environmental responsibility among manufacturers, yet it remains constrained by structural, financial, and institutional challenges. Strategies such as cleaner production, technological upgrades, adoption of renewable energy, employee training, and partnerships with environmental agencies are increasingly implemented, demonstrating a commitment to sustainable industrial practices.

However, adoption remains uneven, largely due to high capital costs, limited technical capacity, low environmental awareness among some stakeholders, and inadequate regulatory enforcement. These barriers echo findings in global studies, which emphasize that technological solutions alone are insufficient without supportive human, financial, and institutional frameworks (Lieder & Rashid, 2016; Moreno et al., 2016).

Cleaner production and technological upgrades in Zambia mirror international evidence showing that preventive approaches targeting pollution at the source are more effective than reactive post-pollution treatment (UNIDO, 2017). Similarly, investments in pollution-control equipment and renewable energy align with the broader literature highlighting the dual benefits of emission reduction and energy efficiency (IEA, 2021). Nevertheless, as observed globally, SMEs often face disproportionate barriers due to the high costs and maintenance requirements of such technologies (OECD, 2019), which help explain the uneven uptake reported in this study.

The study's emphasis on employee training and capacity building resonates with scholarship underscoring the importance of human capital in implementing sustainability initiatives (Lozano, 2015). Trained personnel are essential for operationalizing technologies, maintaining compliance, and fostering a culture of environmental stewardship. Likewise, partnerships with regulatory agencies and NGOs reinforce findings from other contexts, suggesting that collaborative governance and multi-stakeholder engagement enhance monitoring, compliance, and the diffusion of sustainable practices (Hartmann & Linnemann, 2008).

Overall, the Zambian experience illustrates that effective pollution mitigation is inherently multi-dimensional. The findings confirm that integrating technology, human capacity, policy support, and circular economy principles create synergies

that maximize environmental outcomes. This aligns with global scholarship emphasizing that successful environmental management requires both top-down regulatory frameworks and bottom-up industry-driven initiatives, supported by financial incentives, knowledge sharing, and institutional coordination (Geissdoerfer et al., 2017; Kirchherr et al., 2018).

### 6. CONCLUSION

The study reveals that Zambian manufacturers have made notable strides in adopting a variety of pollution mitigation strategies to reduce the environmental impact of industrial activities. Key interventions include reuse, recycling, and remanufacturing initiatives, which are integral components of circular economy practices. Cleaner production and technological upgrades, such as energy-efficient machinery, closed-loop water systems, and the substitution of hazardous materials with eco-friendly alternatives, further demonstrate the sector's commitment to environmental sustainability.

Additionally, integrating renewable energy solutions, including solar thermal and photovoltaic systems, reduces reliance on diesel generators, thereby lowering greenhouse gas emissions and improving energy security. Employee training and capacity-building programs are also crucial, ensuring that staff are well equipped to operate pollution-control equipment, implement waste-minimization practices, and adhere to environmental guidelines.

Despite these positive developments, the study highlights several persistent challenges that limit broader adoption and effectiveness. Financial constraints, particularly among small and medium-sized enterprises, hinder investment in advanced pollution-control technologies and renewable energy systems. Outdated equipment and limited technical expertise further reduce the efficiency of mitigation efforts. Weak regulatory enforcement and fragmented policy frameworks create additional barriers, as firms may lack incentives or support to fully implement sustainable practices.

To achieve scalable and long-term improvements, it is essential to strengthen policy coherence, harmonize environmental regulations, and enhance monitoring mechanisms. Expanding access to green financing and subsidies can lower the cost barriers for manufacturers seeking to adopt cleaner technologies. Capacity-building programs should be intensified to target both technical skills and environmental awareness. Finally, fostering public-private partnerships can facilitate knowledge sharing, technical support, and collaborative compliance initiatives, creating a more integrated approach to pollution mitigation. In conclusion, while Zambian manufacturers have demonstrated commitment to sustainability, coordinated policy action, financial support, and institutional capacity building are critical to ensuring that pollution mitigation strategies are both effective and widely implemented across the sector.

## 7. RECOMMENDATIONS

### 7.1 Policy and Regulatory Strengthening

- Harmonize and enforce environmental regulations to ensure consistent compliance across the manufacturing sector.
- Introduce clear guidelines for pollution control, circular economy practices, and cleaner production standards.
- Strengthening the capacity of regulatory institutions such as ZEMA and ZABS through increased funding, staffing, and modern monitoring equipment.
- Implement mandatory environmental reporting and auditing requirements with penalties for non-compliance.

### 7.2 Financial Incentives and Green Financing

- Expand access to grants, subsidies, and low-interest loans for firms adopting cleaner production technologies and renewable energy solutions.
- Encourage investment in pollution-control equipment through tax incentives and public-private financing mechanisms.
- Establish a dedicated green financing facility targeting SMEs to support technology upgrades and sustainable practices.
- Develop carbon credit programs that allow firms to monetize emission reductions.

### 7.3 Capacity Building and Human Resource Development

- Implement regular training programs for employees on environmental management, resource optimization, safe chemical handling, and sustainability practices.
- Promote knowledge-sharing platforms and workshops to enhance technical capacity among SMEs and larger firms.
- Integrate environmental management modules into technical and vocational training curricula.
- Establish industry-wide certification programs for environmental management professionals.

### 7.4 Technology Adoption and Cleaner Production

- Support the transition to energy-efficient machinery, closed-loop water recycling systems, and eco-friendly materials.
- Facilitate access to modern pollution-control equipment, such as effluent treatment plants, air scrubbers, and emission capture systems.
- Establish technology demonstration centers where firms can assess and trial cleaner production technologies.
- Promote research and development partnerships between industry and academic institutions.

### 7.5 Renewable Energy Integration

- Encourage investment in solar and other renewable energy systems to reduce dependence on diesel generators and lower operational emissions.

- Provide technical and financial support to firms seeking to implement renewable energy solutions.
- Develop feed-in tariff schemes or net metering policies to incentivize on-site renewable energy generation.
- Support the development of renewable energy service companies to assist manufacturers with system design, installation, and maintenance.

### 7.6 Strengthening Partnerships and Collaboration

- Foster collaboration with regulatory agencies, NGOs, industry associations, and international partners to improve monitoring, compliance, and advisory support.
- Promote joint initiatives for environmental auditing, sustainability standard development, and capacity enhancement.
- Establish industry-led sustainability councils to facilitate peer learning and collective action.
- Strengthen public-private dialogue platforms to address regulatory bottlenecks and share best practices.

### 7.7 Promoting Circular Economy Practices

- Encourage reuse, recycling, and remanufacturing as core strategies in industrial operations.
- Develop incentive schemes to reward firms that demonstrate measurable reductions in waste and resource consumption.
- Establish regional recycling hubs and waste processing facilities to support circular economy initiatives.
- Implement extended producer responsibility frameworks to hold manufacturers accountable for end-of-life product management.

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